Voyager Interstellar Mission

Proposal to Senior Review 2005 of the Mission Operations and Data Analysis Program for the Sun-Solar System Connection Operating Missions

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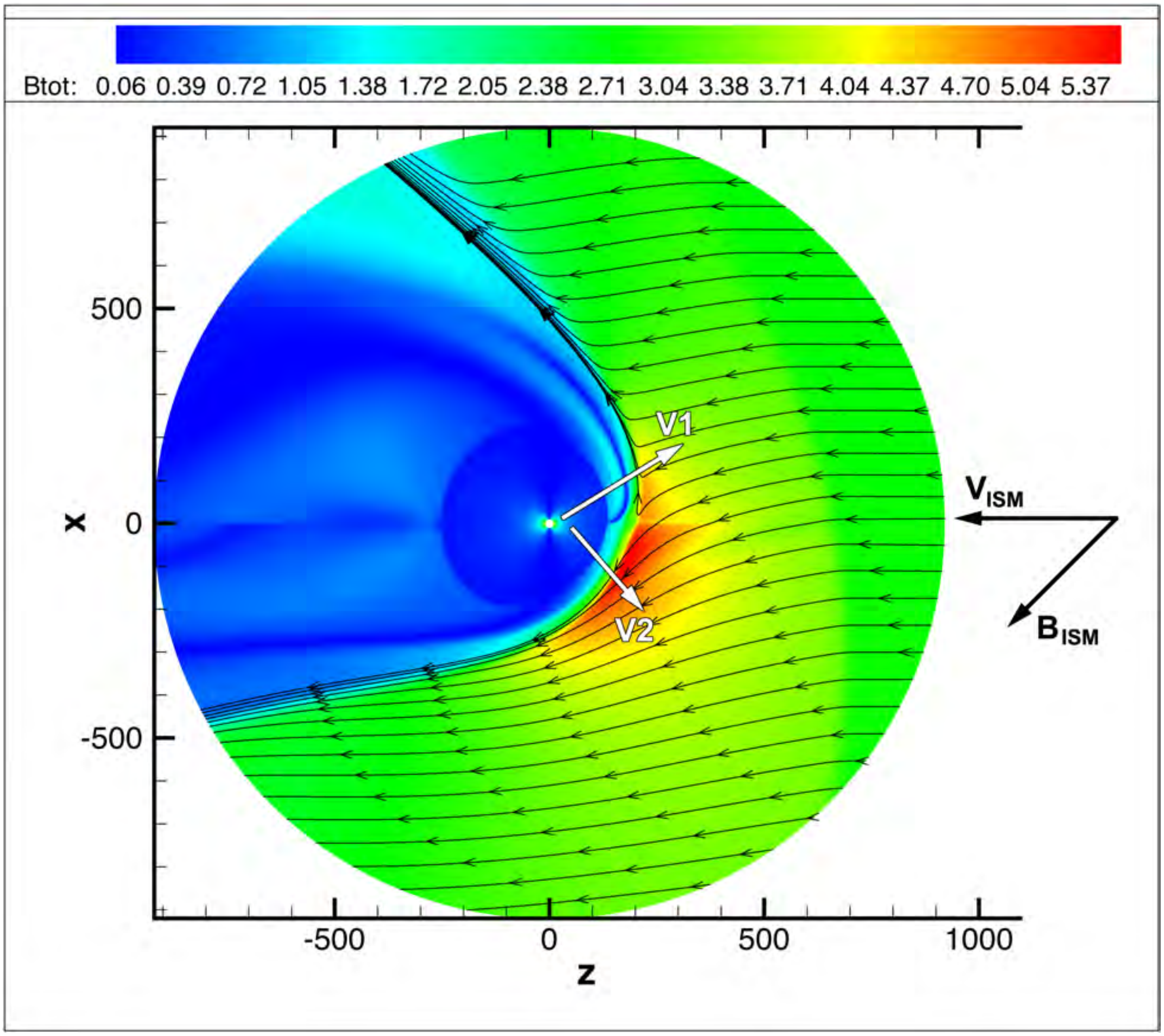

Model from Pogorelov et al. 2004

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EXECUTIVE SUMMARY

The Voyager Interstellar Mission is exploring the interaction of the heliosphere with the local interstellar medium (LISM). Voyager 1 (V1) crossed the termination shock (TS) in December 2004 and is making the first measurements in the heliosheath (HSH). The crossing of the TS provided the first concrete information on the scale size of the heliosphere; based on the TS distance, the heliopause (HP) and LISM are probably 30-40 Astronomical Units (AU) further out. Although the uncertainties in the HP position are large, the Voyager spacecraft have a good chance of reaching this boundary in their operational lifetimes. Thus the Voyagers should provide the first direct observations of the LISM.

Voyager 2 (V2) has detected energetic particle intensity increases similar to those observed by V1 from mid-2002 to the TS crossing; these increases are precursors of the TS. Thus V2 is likely to cross the TS in the next few years. The V2 TS crossing will result in the first plasma measurements at the TS and in the HSH and set limits on hypothesized heliospheric asymmetries.

The TS approach and crossing provided many surprises. The intense, highly variable, anisotropic beams of energetic particles observed for 2.5 years upstream of the TS were unexpected. These beams indicated that a persistent magnetic connection was maintained between V1 and the TS and suggests that the TS and heliosphere are asymmetric. Another surprise was that the anomalous cosmic rays (ACRs) are still modulated in the HSH; although the lower energy ions making up the precursor beams are accelerated at the shock, the ACRs are not, at least not in the region crossed by V1. ACR acceleration may be limited to favored regions of the TS or may occur further out in the HSH. Another surprise is the magnetic field; before the TS, V1 was seeing polarity changes as it crossed the heliospheric current sheet (HCS); after the TS crossing, V1 remained in the southern polarity sector for 110 days even though it is at northern heliolatitudes. The inferred plasma flow is unexpectedly low and variable, and the pickup ions are strongly heated. None of the foregoing observations were anticipated by theory, so these and future V1 revelations of the unexpected nature of the HSH will drive theoretical modeling towards a new paradigm.

Future work encompasses several tasks. Inside the TS, V2 will study solar wind (SW) evolution and interaction with the LISM and, in particular, how the SW slows before the TS. At the next solar minimum, V2 may be at a high enough latitude to monitor the interaction region between the fast and slow SW and to observe coronal hole flow at large distances. V2 will observe the beams of upstream energetic ions from the TS at a different location and geometry from V1, which should help illuminate the ion source and the possible heliospheric asymmetries. The location of the V2 TS crossing will shed light on the overall shock morphology, especially combined with data from the IBEX mission. V2 plasma data at the TS will help us understand the TS physics and structure. We will observe the recovery of cosmic rays beyond 100 AU at solar minimum, determine the effects of a negative magnetic polarity solar cycle, monitor the unfolding of the low energy ACR spectra as V1 moves through the HSH and V2 crosses the TS, and search for additional bursts of heliospheric radio emission.

1. INTRODUCTION

The Voyager spacecraft were launched in 1977 on a trajectory toward the giant planets. Fortunately, the Voyagers are headed toward the upstream direction of the heliosphere. After the successful planetary encounters, the Voyager Interstellar Mission continued outward with the goal of making the first observations of the LISM. V1 has now crossed the TS, so the goal of reaching the LISM seems achievable.

The cover figure shows a schematic diagram of the heliosphere/LISM interaction (modified from *Pogorelov et al.*, 2004). The LISM moves past the Sun with a speed of 26.4 km/s. The Sun ejects the SW with a speed of 400-700 km/s. The HP is the boundary between the SW plasma and the LISM. At this boundary, as shown by the flow lines in the figure, the LISM plasma flow diverts around the heliosphere and the SW rotates to flow toward the heliospheric tail. Since the SW and LISM are supersonic, shocks form in both flows before they reach the HP. At these shocks, the plasma is slowed, compressed, heated, and initiates the change in direction. Depending on the direction of the LISM magnetic field, large asymmetries may be present in the heliospheric structure.

V1 crossed the TS, where the SW becomes subsonic, in December 2004 at 94 AU. This crossing set the scale for the whole heliospheric system; the missing piece before this crossing was the pressure in the LISM; knowing the TS boundary distance fixes this parameter. Models predict that the HP is 30-40% more distant than the TS. The Voyager trajectories are shown in Figure 1; distance in AU is plotted vs. heliolatitude and times are marked on the trajectory traces. Also marked are the locations of the V1 TS crossing and the probable locations of the V2 TS crossing and the V1 and V2 HP crossings based on model results (see section 4). Models which incorporate solar cycle pressure changes suggest that the V2 TS crossing should occur within a few years. V2 has detected TS precursors similar to those that V1 observed before the TS crossing. The V1 HP crossing is likely to occur near or after 2015 and the V2 HP crossing in a similar time frame. The spacecraft will have sufficient power to operate all instruments until 2016; after this time, power-sharing will extend the useful life of the spacecraft until at least 2020. Thus the Voyagers are likely to provide the first in situ measurements of the LISM.

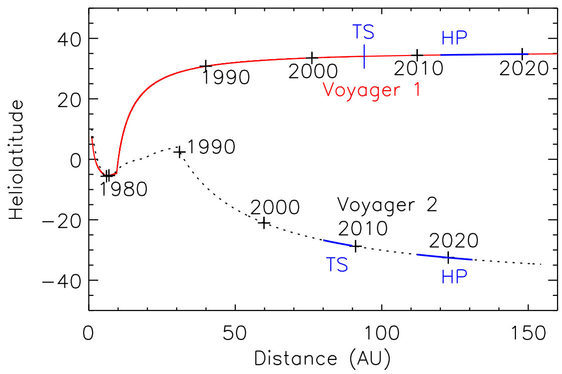

FIGURE 1. Trajectories of the Voyager spacecraft.

Before they reach the LISM, the Voyager spacecraft will explore an entirely new region, the HSH. This region of subsonic flow should be active, containing both structures entrained in the SW and those generated by the motions of the TS. This region contributes to the modulation of the galactic cosmic rays (GCRs) [*McDonald et al.*, 2002]. Already unexpected attributes are being discovered, such as the temporary cessation of sector boundary crossings, a large meridional magnetic field, and an increase of ACR intensities with distance.

The Voyager spacecraft are relatively healthy. The active instrument teams are the Plasma Science experiment (PLS) which measures thermal plasma, the Low Energy Charged Particle experiment (LECP) which detects particles in the tens of keV to tens of MeV range, the Cosmic Ray subsystem (CRS) which measures GCRs and ACRs, the magnetometer experiment (MAG), and the Plasma Wave subsystem (PWS) which observes plasma and radio waves. In addition, the Planetary Radio Astronomy and Ultraviolet Spectrometer instruments still return data, although the science teams are not supported. The V1 PLS experiment failed soon after the Saturn encounter in 1980 and has not been able to detect even the higher plasma fluxes expected in the HSH. The V2 PWS still returns valuable data in many channels; however, the wideband receiver failed in 2003, the 17.8 Hz channel is intermittent, and the upper 8 channels (1 kHz to 56 kHz) have decreased sensitivity due to a failure in a multiplexor switch in the FDS. The V2 MAG experiment has a continuing problem with noise generated by the spacecraft and other instruments which makes reliable analysis very difficult, but the higher magnetic field strength at solar maximum (and soon the higher magnetic field strength in the HSH) has made that problem more tractable. Otherwise the instruments work well and all have the sensitivity to continue observations in the environments expected beyond the TS and HP.

The Sun-Solar System Connection Science and Technology Roadmap 2005-2035 sets forth NASA's goals, some of which depend critically upon data from the Voyager spacecraft. The first Sun-Solar System Connection (SSSC) objective is to "Understand the fundamental processes of the space environment - from the Sun to Earth, to other planets, and beyond to the interstellar medium". The Voyagers are the only spacecraft positioned to directly observe the boundaries of the heliosphere and have a chance to directly sample the LISM. These boundaries are the largest features in the heliosphere and allow us to study physical processes such as magnetic reconnection, particle acceleration and transport, and the interaction of the SW plasma with the LISM neutrals in a system with very large scale sizes. These three topics, magnetic reconnection, particle acceleration and transport, and plasma-neutral interactions, are priority research focus areas identified by the SSSC roadmap. The unique perspective of the Voyagers is crucial for these studies. In addition, a priority investigation identified in the roadmap, F3.4, is "How do the heliosphere and the interstellar medium interact"? The role of Voyager in answering this question is clearly critical.

The recent scientific discoveries bearing on these roadmap objectives are elaborated on in this proposal. They include the first crossing of the TS, the first observations of the HSH, the slowdown of the SW due to interaction with the LISM neutrals, the discovery of energetic particles streaming upstream of the TS, and the lack of the expected ACR acceleration at the TS.

Voyager plays a critical role, and benefits greatly from, its place in the great heliospheric observatory. Voyager provides direct observation of ACRs near their source region and of GCRs before they are modulated in the SW. Comparison of 1 AU and Ulysses data with Voyager data provides a test of models of SW evolution. Inner heliospheric spacecraft provide needed baseline data to determine how the SW is affected by LISM neutrals as it travels through the heliosphere. For example, to determine how much the SW is slowed by pickup of the LISM neutrals we must know the SW speed at a similar latitude in the inner heliosphere. The Voyagers observe the integrated effects of SW evolution and interaction with the LISM from the inner to outer heliosphere. The inner heliospheric spacecraft do the reverse, observing the integrated effects of inward motion of ACRs and GCRs and LISM neutrals from the LISM and TS to 1 AU. These complementary data sets allow us to test models, providing input conditions at one boundary and benchmark observations at the other.

When the Interstellar Boundary Explorer (IBEX) spacecraft joins the SSSC great heliospheric observatory, the synergy with Voyager data will be even greater. IBEX will measure the heliospheric boundaries by observing energetic neutral atoms. These observations will provide a global picture of the Sun-LISM interaction at the same time the Voyager spacecraft are exploring two pieces of the interaction in situ. The global picture will be of great help for understanding the in situ observations and vice versa.

The sections which follow describe five broad science topics being addressed by the Voyager spacecraft. These topics are 1) the SW, TS precursors and the TS crossing, 2) the HSH, 3) the HP and interplanetary medium, 4) energetic neutral atoms, and 5) cosmic ray modulation. For each topic we give a description of the science, summarize recent results, and describe how Voyager data will advance our knowledge in these areas in the future.

2. THE SW, TS PRECURSORS AND THE TS CROSSING

V1 was crossed by the SW TS on DOY 351 (Dec. 16) of 2004 at a helioradius R=94.0 AU and a heliolatitude λ=N34.1° [*Stone et al.*, 2005; *Decker et al.*, 2005; *Burlaga et al.*, 2005; *Gurnett and Kurth*, 2005]. The hundred-fold increase in energetic particles seen in mid-2002, together with a dramatic reduction in their radial anisotropy, led *Krimigis et al.* [2003] to suggest an the TS had been crossed and later recrossed. However, the magnetic field, especially at the second boundary, was not consistent with these boundaries being the TS [*Burlaga et al.*, 2003; *Ness et al.*, 2005]. In retrospect, this event was likely the foreshock boundary [*Decker et al.,* 2005].

V1 has remained in the HSH, the shocked SW outside the TS, until at least DOY 248 of 2005 (at this writing). This section summarizes measurements of energetic particles and plasma waves at V1 from mid-2002 to the TS crossing, of energetic particles and SW at V2 from 2003 to date, and describes predictions of when V2 will cross the TS. Magnetic field data from V1 in the SW and HSH are discussed in Section 3.

The TS is where the SW plasma makes its transition from super- to sub-magnetosonic flow. The SW plasma is compressed and heated and the magnetic field strength increases. To prepare for the Voyager TS encounters, *Zank* [1999] reviewed the predictions of the nature and location of the TS. Since the average spiral magnetic field upstream of the TS is along the $\pm$T axis (where R is outward from the Sun and T is in the solar equatorial plane and positive in the direction of the Sun's rotation), the TS is expected to be a quasi-perpendicular shock. However, energetic particles accelerated or re-accelerated at the TS and possibly in the turbulent HSH can propagate into the upstream region. When the Voyager spacecraft are near the TS and connected to it by the magnetic field, measured particle intensities and anisotropies may be comparable to those at the TS if pitch angle scattering is infrequent over the connection length and particles can traverse this length before being convected shockward. Otherwise, intensities and anisotropies observed at Voyager will be reduced relative to those at the TS.

2.1 V1 Observations in the Vicinity of the TS

Figures 2 and 3 show energetic particle observations at V1 from 2002 through mid-2005. The upstream (pre-TS crossing) intervals denoted as A and C in Figure 2(a) and as TSP1 and TSP2 (Termination Shock Particles) in Figure 3b correspond roughly to the same two periods. Interval A/TSP1 has been analyzed in detail [*Krimigis et al.*, 2003; *McDonald et al.*, 2003; *Burlaga et al.*, 2003a] and study of interval C/TSP2 continues [*McDonald et al.*, 2004; *Krimigis et al.*, 2004, 2005]. During these periods, large increases in the intensities and in the intensity variations of >40 keV ions and >26 keV electrons (not shown) are observed as are large anisotropies in the angular distributions of 40 keV to 30 MeV ions. Intensities of lower energy ions (40 to ~500 keV) increased across the TS and their profiles in the HSH remained relatively flat and smooth compared to those in the supersonic solar wind (SSW). Intensities of higher energy ions (>500 keV) and electrons (>26 keV) are also relatively smooth in the HSH, but continue to increase steadily, due possibly to decreasing modulation or to intensity gradients in the HSH. Upstream angular distributions of ions showed unidirectional, field-aligned beams [*Decker et al.*, 2004] directed mainly outward away from the sun in a near-azimuthal direction, i.e., along the -T axis (Figures 2(b) and 3(b)). Downstream anisotropies are markedly reduced compared to those upstream. Angular distributions of low-energy ions in the SSW and HSH have been used estimate the plasma flow speeds shown in Figure 2(f) [*Decker et al.*, 2005; *Krimigis et al.*, 2005]. Estimates of the radial component of the HSH plasma flow velocity based on these data are discussed in Section 3.

Before the V1 observations, we expected that particle streaming along the interplanetary magnetic field

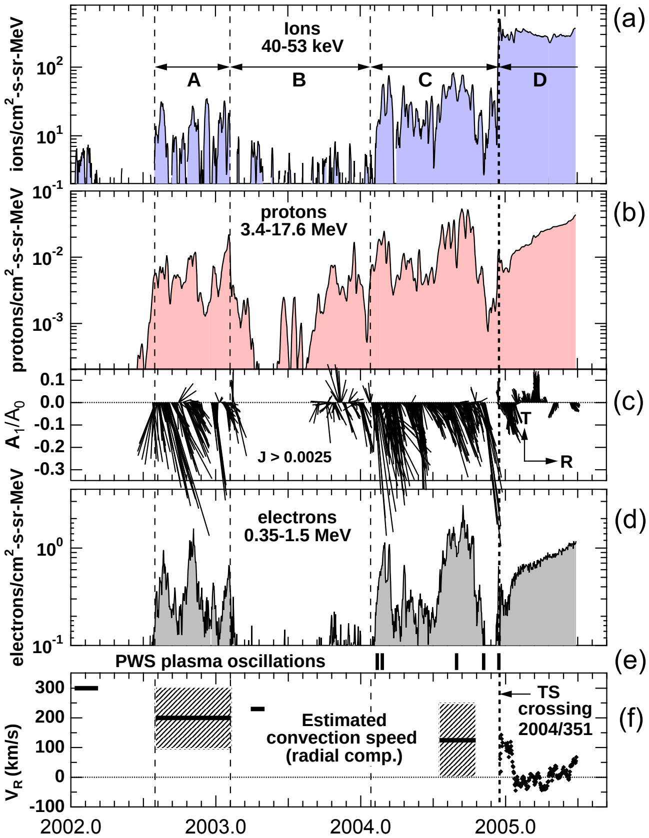

FIGURE 2. V1/LECP data during 2002.0-2005.7 (83.4-97.0 AU). (a), (b), and (d): Background-corrected, scan-averaged 5-day smoothed daily-averaged intensities of 40-53 keV ions, 3.4-17.6 MeV protons, and 0.35-1.5 MeV electrons. (c): First-order anisotropy vector $\mathbf{A}_1/A_0$ of proton channel in (b) when the intensity >0.0025 flux units (inset shows orientation of **R** and **T**). Whiskers show direction that particles are traveling. (e): Black bars show times when the V1 PWS detected electron plasma oscillations [*Gurnett and Kurth*, 2005]. (f): Estimated plasma radial flow speed V_R based on 40-220 keV ion angular data and a velocity extraction algorithm [*Krimigis et al.*, 2005]. Bounds on V_R during period A and the second half of period C (2004.56-2004.78) are indicated by the cross-hatched rectangles and means are shown by the horizontal bars. V1 MAG vector data were used in the V_R extraction algorithm for the period 2004.000-2005.164. Horizontal bars during 2002.041-2002.172 and 2003.257-2003.322 are from *Krimigis et al.* [2003].

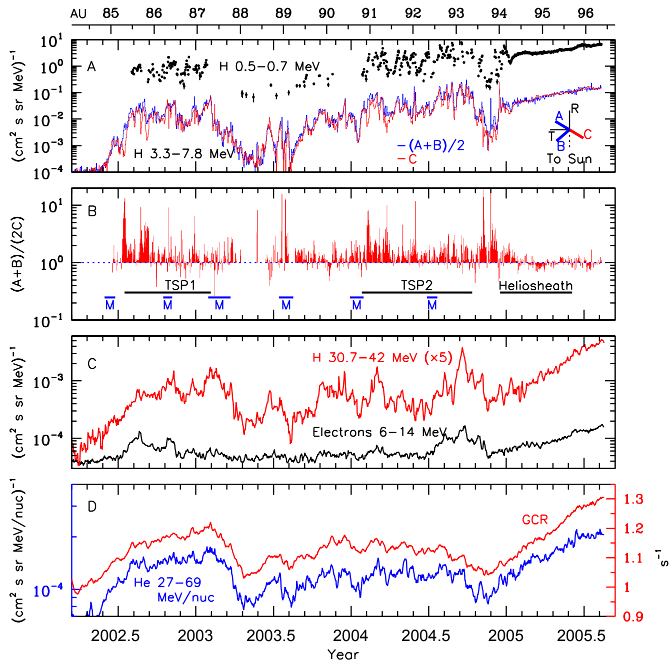

FIGURE 3. (A) Intensities of TSPs. Inset illustrates the telescope viewing directions projected into the R-T plane. Particle telescopes A and B measure 3.3-7.8 MeV protons streaming outward along the spiral magnetic field in the -T direction and telescope C observes those moving in the opposite direction. The intensity of 0.5-0.7 MeV protons observed by telescope A is shown when the background correction was <60%. V1 crossed the shock and entered the HSH on 2004.96 (Dec. 16). (B) Azimuthal streaming index as indicated by the ratio of the average daily intensity in telescopes A and B to that in C. Upstream of the shock there were two periods of upstream episodes of enhanced intensities (TSP1 and TSP2) during which streaming anisotropy was usually large and mainly in the -T direction. The streaming anisotropy is much smaller in the HSH. Merged Interaction Regions (labeled M) are indicated (20). (C) Intensities (five-day moving averages) of ~10 MeV electrons and ~35 MeV H. These increases are strongly correlated and of shorter duration than for lower energy H. (D) Intensities (five-day moving averages) of He ions and of GCRs with E>70 MeV/nuc. The He intensity is due mainly to ACRs.

(IMF) upstream of the shock source would be inward along the spiral field. The observed outward streaming requires the acceleration region (the TS) to be several AU closer to the Sun than V1 and in the +T direction. The spiral IMF crosses the TS and then recrosses it and returns to the SW before reaching V1; thus the magnetic field line connects V1 to the TS. This geometry requires a non-spherical TS. *Jokipii et al.* [2004] suggested that the nose of the TS is flattened due to the pressure of the interstellar wind. Alternatively, an inclined interstellar magnetic field could cause an asymmetrical distortion of the shock [*Ratkiewics et al.*, 1998] and produce the required geometry. Recent observations and modeling suggest that the heliosphere may be quite asymmetric, with the TS further from the Sun in the direction of V1 (see Section 4 for a discussion of the asymmetry). Thus, as deduced from the TSP observations, V1 would be connected to the TS by the IMF long before crossing this boundary.

Figure 4 shows that the energetic H and He spectra have three distinct components in the HSH. The TSP component dominates at lower energies, ACRs dominate the He component at intermediate energies, and GCRs dominate at higher energies. Before V1 crossed the TS, the TS was thought to be the ACR source. The predicted spectrum at a strong TS shock (the compression ratio across the shock, also called the shock strength, $r = 4$) is shown by the dashed line and at a weak TS ($r = 2.4$) by the dotted line, These spectra were determined from model fits to the Voyager observations during the most recent solar minimum [*Cummings et al.*, 2002].

The TSP energy spectra appear to be broken power laws that can be represented by $j = j_0(E/E_{norm})^a$ for $E \leq E_0$ and by $j = j_0(E_0/E_{norm})^{(a-b)}(E/E_{norm})^b$ for $E > E_0$, where E_0 is the break energy. This spectral form was fit to daily averaged proton intensities. During the upstream TSP events, the spectral slope was variable, typically ranging between -1 and -2 as propagation conditions changed along the magnetic field line connecting V1 to the shock. The break energy, however, showed little variation and is the same before and after the TS, suggesting that it is a characteristic of the TS source.

The spectra of the TSP ions in the HSH are much less variable, with a mean spectral slope at low energies $< a >= -1.41$ and an rms of 0.15 for the period 2005/90-156. The steadiness of the spectrum suggests that the spectral shape is little affected by modulation in the HSH, as expected [*Jokipii and Giacalone*, 2004]. The shock strength r can be determined from the spectral slope, $r = (2a+2)/(2a-1)$. The observed mean and rms values for $< a >$ indicate that the TS strength is $2.6^{+0.4}_{-0.2}$. Thus the TS is weak when averaged over the timescale for TSP acceleration. This average shock strength is consistent with that inferred from the V1 MAG data [Section 3; *Burlaga et al.*, 2005a].

V2 was at R=76.8 AU and λ=S26.1° on day 180 of 2005. V2 will observe a different region of the TS than V1 (R=94.0 AU and λ=N34.1° at the TS crossing). We will compare V2 TSP spectra with spectra from V1 in the HSH to determine if a common TSP spectrum is a characteristic of the TS. Any differences could be indications of different conditions at the two shock locations.

Figure 5 shows data near the TS crossing on DOY 351. In Figure 5(a) the ion and electron angular data on DOY 350 show a highly anisotropic shock spike in the immediate upstream vicinity of the TS (the TS crossing evidently occurred on DOY 351, when no data were obtained due to a tracking gap). Data in the upper panel of (a) imply a proton anisotropy (S3-S7)/(S3+S7)≈0.92 during hour 0900 and those in the lower panel an electron anisotropy ≈0.16 during hour 1900. This intensity spike is unusual not only for its short duration and intense beaming, but also because the ions and electrons are streaming sunward along the magnetic field, which on DOY 350 had a projection onto the LECP scan plane that was lying nearly along the line separating sectors 3 and 4. Also, in contrast to the ions, angular distributions of 0.35-1.5 MeV electrons have been nearly isotropic through the 2.5 yr pre-TS and 0.6 yr post-TS periods.

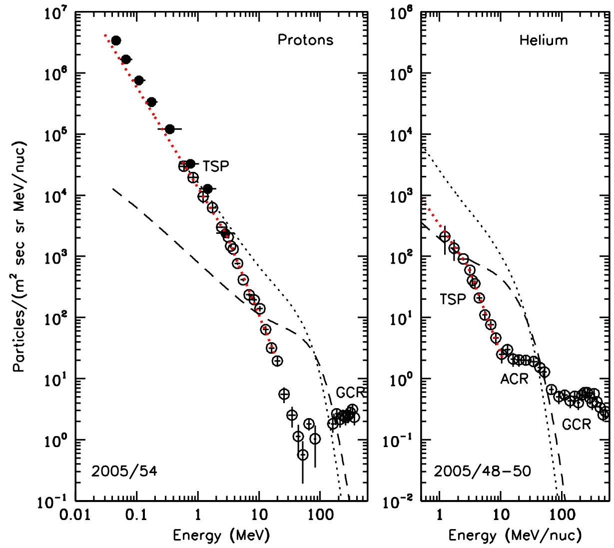

FIGURE 4. Typical spectra observed in the HSH. The solid circles in the left panel are background-corrected ion (Z≥1) intensities from the LECP instrument. Other points are from the CRS instrument. The spectrum of TSPs is a broken power law with break energy of ~3.5 MeV for protons and a helium. ACR helium dominates the mid-energies in the right panel, with GCRs at higher energies in both panels. The predicted ACR spectra at the shock are shown for a strong (r=4) and a weak (r=2.4) shock [*Cummings et al.*, 2002]

Figure 6 shows electron plasma oscillations (Langmuir waves) measured on DOY 350 by the PWS instrument [*Gurnett and Kurth*, 2005]. Planetary bow shocks and interplanetary shocks sometimes generate energetic electrons beams which flow upstream through the SW and generate electron plasma oscillations. These observations led Kurth and Gurnett [1993] to predict that electron plasma wave oscillations would be present upstream of the TS. These waves were first observed on February 11, 2004, at 91 AU, and continued sporadically with a gradually increasing occurrence rate for nearly a year (Figure 2(e)). The last event occurred on DOY 350 of 2004, just before the spacecraft crossed the TS. No further electron plasma oscillations have been observed, consistent with the spacecraft having crossed the TS into the HSH. The observation of an upstream electron beam coincident with the electron plasma oscillations on DOY 350 provides strong evidence that the plasma oscillations are being driven by energetic electrons from the TS. In analogy with planetary bow shocks, *Gurnett and Kurth* [2005] suggested that just before passing through the TS the spacecraft passed through a region where the magnetic field is nearly tangent to the surface of the shock, as illustrated in the lower panel of Figure 6. The tangent field condition could be caused either by waviness of the shock boundary or by complex variations in the magnetic field geometry.

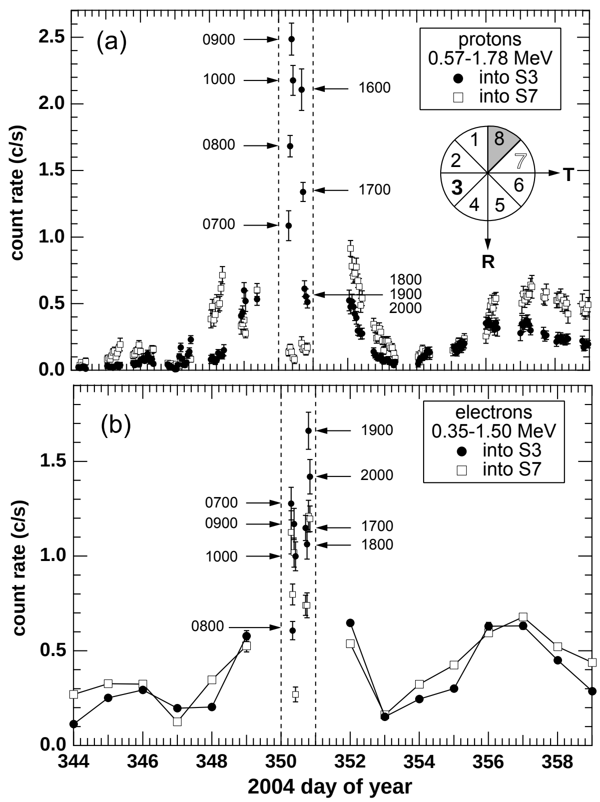

FIGURE 5. Angular count rate data during 2004 DOY 344-359 for (a) 0.57-1.78 MeV protons and (b) 0.35-1.5 MeV electrons, with hourly-averaged data on DOY 350 (dashed vertical lines). Inset pie plot in panel (a) shows view directions of the eight 45° sectors in the LECP scan plane, which is nearly parallel to the local R-T plane.

Observations from the SWICS and HISCALE instruments on Ulysses (1-5 AU) were combined with those from V1 (94 AU) to examine how effectively the TS accelerates particles. Figure 7 compares Ulysses SW and pickup proton spectra extrapolated to ~95 AU with measurements of the proton spectra made by the V1 LECP instrument [*Gloeckler et al.*, 2005]. The resulting pickup H^+ spectrum matched the observed V1 spectrum extremely well. Pickup ions dominate above ~100 eV downstream of the TS and ~20 keV upstream of the TS, consistent with composition measurements [*Krimigis et al.*, 2005]. Pickup and SW ions, which are heated by the same fractional amount at the shock, have sufficient injection energy to be accelerated into the tail portions of the spectra. Over 80% of the energy available from the ram pressure of the SW heats and accelerates pickup ions; the other 20% heats and

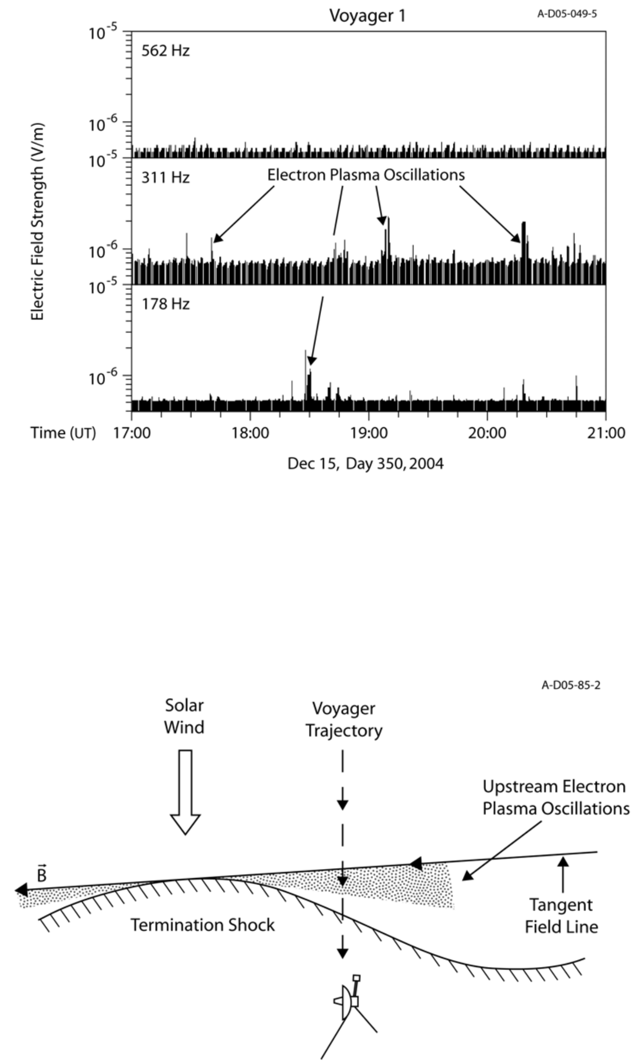

FIGURE 6. (top) Electric field intensity of electron plasma oscillations observed on Dec. 15, 2004, just before the TS crossing. This event is coincident with the anisotropic 0.35 to 1.5 MeV electron beam in the bottom panel of Figure 5. The plasma oscillations occur in short bursts, with durations of a few minutes or less, very similar to the February 11-15 event [*Gurnett and Kurth*, 2005]. Note that the plasma oscillation frequency shifts down to 178 Hz at about 18:30 UT, indicating that the electron density decreased from about 1.2 x 10^{-3} cm^{-3} to about 3.9 x 10^{-4} for a short time around 18:30 UT. (bottom) Detection of the anisotropic electron beam by the LECP instrument just ahead of the TS and coincident with the electron plasma oscillations observed on Dec. 15 suggests that the spacecraft passed through a region (shown shaded) where the IMF is nearly tangent to the TS surface. High beam velocities are expected in this region, so conditions are favorable for generating electron plasma oscillations.

accelerates the SW. The downstream convective speed (∼28 km/s) needed to fit the computed spectra to the LECP data implies inward motion of the shock at 55 km/s (∼12 AU/year) at the time of the TS crossing by V1. Since measurements of ions in the suprathermal range (a few keV to ∼40 keV) are not available from either of the Voyagers, these extrapolated distributions could be used to model the acceleration of ions and the production of energetic neutral atoms (ENAs) beyond the TS (see Section 5).

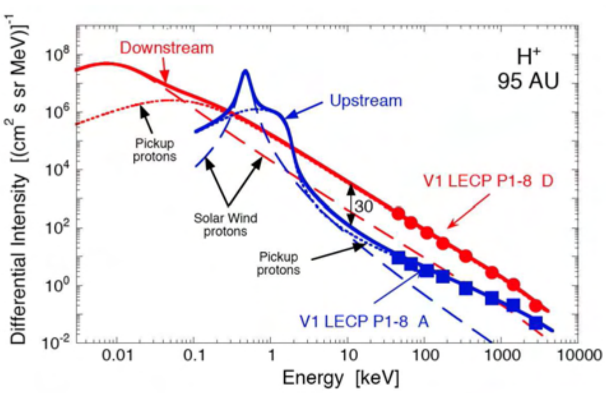

FIGURE 7. Differential intensities of H^+ upstream and downstream of the TS. Heavy curves represent the combined SW (dashed curves) and pickup proton (dotted curves) spectra. Filled squares and circles are the ion spectra measured by the LECP instrument upstream (A) and downstream (D) of the TS. The acceleration efficiency of the TS, defined as the ratio of the downstream to upstream suprathermal ion intensity, is ∼30 [*Gloeckler et al.*, 2005].

2.2 V2 Observations in the Solar Wind Upstream of the TS

The next few years will mark the transition to solar minimum in 2007 or 2008. At the last solar minimum in 1996, V2 was at heliolatitude λ=S16° and saw a peak speed of 570 km/s, indicating that V2 did not enter the fast coronal hole flow but remained in the transition region between slow and fast SW. This result was consistent with the estimate that the half-width of the slow wind region was about 15° in 1996 [*Richardson and Paularena*, 1997]. At the next solar minimum, V2 will be at λ=S26° and should enter the high-speed solar flow. This event will provide a unique opportunity to investigate the evolution of the fast SW. Of particular interest will be the temperature. Since the fast SW speed is nearly constant, much less stream interaction/shock heating should occur and most of the proton energy we observe should be from the interaction with pickup ions. Recent work predicts that the heating of the SW is proportional to the SW speed [*Smith et al.*, 2005; *Isenberg*, 2005] and the expected observations will test these hypotheses.

V2 should also spend an extensive period within the velocity shear zone, the transition between the fast and slow SW regimes. The velocity shear, together with compressive effects, may produce a heliospheric vortex street [*Burlaga*, 1990; *Goldstein et al.*, 2002]. The vortex street would produce oscillating north-south flows with a period of about 26 days such as those observed in the Voyager data during the past two solar minima [*Lazarus et al.*, 1988; *Burlaga and Richardson*, 2000]. The velocity shear may operate to mix the fluids, particularly since the stabilizing influence of the field is reduced when the magnetic field is perpendicular to the velocity. In that case, we would expect a turbulent region, with perhaps substantial heating of the plasma and energetic particles. Since Ulysses will be at the same southern latitude as Voyager at this time, we will have an opportunity to see how the shear regions evolve from Ulysses to Voyager 2.

This latitudinal alignment between Ulysses and V2 will allow study of other aspects of SW evolution, in particular of the speed decrease due to pickup ions. The SW plasma ionizes interstellar neutrals, which are then accelerated to the SW speed and heated to a thermal energy equal to the SW energy, about 1 keV. The energy for this acceleration and heating comes from the bulk motion of the SW and thus the SW speed decreases. Determination of the SW deceleration requires a difference measurement between the SW speed in the inner heliosphere (at Ulysses or a spacecraft near Earth) and at the distance of V2. Magnetohydrodynamic (MHD) modeling is used to predict the speed expected at V2 based on SW parameters in the inner heliosphere, then the density of the interstellar H is adjusted so that the model results match the observations. These calculations can be performed only when two spacecraft are at the same heliolatitude or near solar maximum, when heliolatitudinal speed gradients are small.

In 1999-2000, near solar maximum, the speed at V2 was 12-14% below that expected in the absence of pickup ions which implies an interstellar H density of 0.09 cm^{-3} at the TS. As the SW moves farther out the deceleration should increase: the next opportunity to estimate the speed decrease will be in 2006, near solar minimum, when both Ulysses and V2 will be at 26°S heliolatitude. Preliminary results from recent data showed a larger slowdown than expected the past two years [*Richardson*, 2005]. If the observations from 2006 confirm this result, the additional speed decrease could result from a change in the interstellar H density at the TS or from increased deceleration from other effects, such as the beams of energetic particles.

Observations as V2 approaches the shock should further constrain the nature of the shock asymmetry.

At V1, the onset of the steady upstream TSP flow began in mid-2002 at 84 AU. The upstream flow continued for $\sim 2\frac{1}{2}$ years until the TS crossing at $\sim$94 AU as the shock moved outward ahead of the spacecraft. The onset, duration, and streaming direction of the TSPs at V2 will help determine the amount and orientation of the distortion of the shock for comparison with improved MHD models of this region of the heliosphere.

The first ion precursor increases at V2 were observed beginning in late 2004 at 75 AU [*Stone et al.*, 2005]. The steady streaming of TSPs thus is either observed at a greater distance upstream of the TS than at V1 or the TS is closer to the Sun in the direction of V2. Figure 8 shows that proton intensities began increasing near 2004.8; the 3.0-17.3 MeV channel displays large anisotropies, with particles streaming mainly in the +T direction, the opposite direction from those observed at V1 from 2002.5 through 2004 (e.g., Figures 2c and 3b). The SW speed is relatively steady at 380-420 km/s. Thus far, the higher energy TS precursor ions are predominant at V2. Intensities of lower energy ions in the 40 to $\sim$200 keV range remain near background, suggesting that V2 is still several AU upstream of the TS.

The absence of a working plasma instrument on V1 necessitated combining angular measurements from low-energy ion channels with models of flow-frame particle pitch-angle distributions to estimate the radial component of plasma flow velocity [*Krimigis et al.*, 2003; *Decker et al.*, 2005]. The large spread in speed estimates for Periods A and C in Figure 2(f) results from the domination of the radial convective component by that of the streaming in the near-azimuthal, anti-sunward streaming and the quasi-recurrent ($\approx$26-day) intensity variations that are present in all ion channels. The eventual detection of enhanced intensities of low-energy ions at V2 combined with the measured flow velocity and vector magnetic field vector will enable us to use V2 data to validate the flow-speed extraction algorithm, and derive improved flow speed estimates at V1 during the period 2002.5 through 2004.

2.3 Predicting the Termination Shock Location

The location of the heliospheric boundaries results from a balance between the dynamic pressure of the outward flowing SW and the total pressure (dynamic plus thermal plus magnetic) of the LISM. The SW dynamic pressure is measured by multiple spacecraft, including V2. The pressure of the LISM has large uncertainties which have limited our ability to predict the TS location. Now that V1 has crossed the TS, we know that the TS distance at V1's position on DOY 351 2004 was 94 AU. We can use this position to normalize models of the TS motion; Figure 9 shows the TS location predicted by a 2-D gas dynamic model which includes the effects of pickup ions. The SW parameters measured by V2 were used as input for the model and the TS location was normalized to match the time of the V1 TS crossing. The TS and V1 moved outward from 2002 to mid-2004, then the TS moved inward across V1, and now V1 is getting farther from the TS.

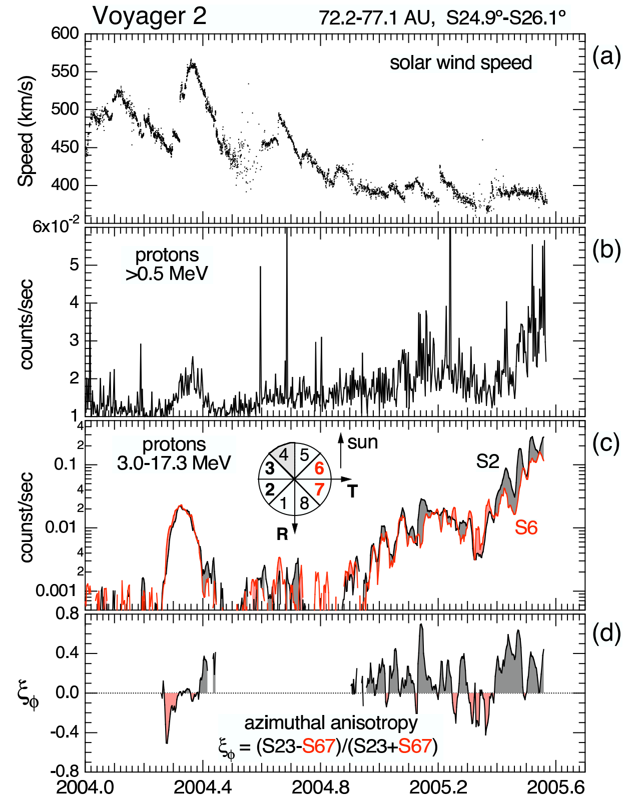

FIGURE 8. V2 PLS SW speed (a), CRS >0.5 MeV proton intensity (b), and LECP 3.0-17.3 MeV proton intensity (c) and its associated azimuthal anisotropy ξ_ϕ (d), during 2004 to 2005.56. ξ_ϕ as defined in panel (d) (see Panel (c) pie plot inset) is a measure of the azimuthal component of the proton streaming anisotropy away from (ξ_ϕ<0) or toward (ξ_ϕ>0) the Sun.

Since V2 has a working plasma experiment, the change in plasma parameters across the shock will be directly measured and provide a better understanding of the TS characteristics. The V1 TS crossing provides a rough estimate of when V2 should encounter the TS. The SW pressures from last solar cycle can be extrapolated forward (dashed lines) and used to model the future TS position at V2. Figure 9 shows that the 2-D model predicts V2 will cross the TS in early 2008 while the static model predicts early 2009. Thus due solely to the inward motion of the TS resulting from solar cycle changes of the SW pressure, we expect V2 to ob-

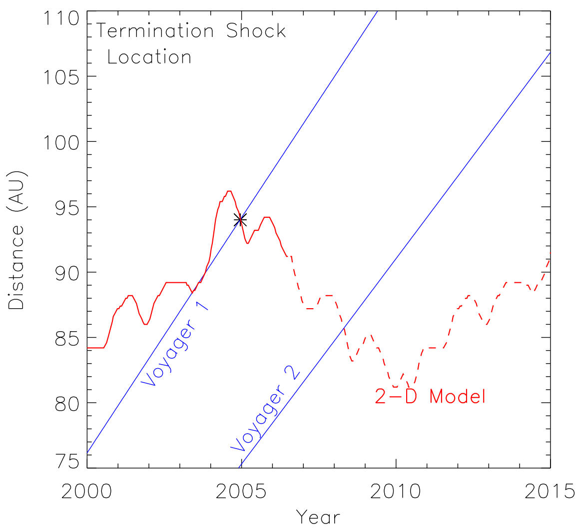

FIGURE 9. Predicted TS location using a 2-D gas dynamic model which includes the effects of pickup ions.

serve the shock in 2.5-3.5 years. Other factors may affect the timing. The TS surface is probably neither spherical nor symmetric with respect to the LISM flow direction. Models predict that the TS will be blunt at the nose [*Zank*, 1999], so spacecraft further from the nose would encounter the TS later. The direction of the magnetic field in the LISM can result in asymmetries of the whole interaction region (see Section 4) Models show the TS and HP boundaries are larger distances at more northerly heliolatitudes; V1 at λ=N34° should thus see the TS at a larger distance than V2 at λ=S26°. The reduction in distance of the TS in the direction of V2 is not known. Precursors to the TS, in the form of streaming energetic particle enhancements, were observed by V1 well before the first TSP event. These events are now being observed by V2. Since the TS was moving outward when V1 saw these events and it is now moving inward, it is possible (perhaps due to this asymmetry) that V2 will cross the TS well before 2008. In any case, the TS location combined with the V2 plasma data will provide information on the magnitude of the TS asymmetry.

Future Work

• Compare V2 TSP energy spectra with spectra from V1 in the HSH to determine if a common TSP spectrum is a characteristic of the TS.
• Combine V2 TS-associated low-energy ion intensities with the measured plasma flow velocity and vector magnetic field to validate and fine-tune flow-velocity extraction algorithms; derive improved SW and HSH flow velocities at V1 from 2002.5 onward.
• Combine TSP ion angular distributions with available SW plasma and IMF data to investigate if ion beam driven hydromagnetic waves could be present. Determine if the Voyager data would detect such TS-associated precursor waves.
• Monitor V1 and V2 PWS data for electron plasma oscillations, which for V2 indicate an approach to the TS and for V1 may indicate a crossing of the TS back into the SW.
• Combine high-time resolution particle and IMF data to examine details of the V1 TS transition. At the V2 TS crossing(s), do the same analysis including plasma data and estimate the key shock parameters for comparisons with simulations and with other observed shocks.

3. THE HELIOSHEATH

V1 has entered the HSH, opening a new phase of heliospheric exploration. The HSH is qualitatively different from the interplanetary medium (IM). The flow is supersonic in the IM but subsonic in the HSH. The velocity is nearly radial in the IM, but in the nose of the HSH it must turn around and move tailward. The magnetic field tends to be axially symmetric about the Sun's rotation axis in the IM, but it tends to be symmetric about the line of the Sun's motion relative to the LISM in the HSH, on a large scale. The gradients and anisotropies of the energetic particles in the IM are different from those in the HSH.

3.1 Energetic Particles in the Heliosheath

The intensities of low energy ions (40-4000 keV) were measured by the LECP experiment on V1 before and after crossing the TS (Figure 10). Before the TS crossing (2004.50-2004.96), the intensities were enhanced, though highly variable, with quasi-recurrent variations with periods of roughly 13 and/or 26 days (light vertical lines are spaced 26 days apart in Figure 10). These enhanced pre-TS ion intensities and superposed fluctuations, as well as associated variations in the spectral indices (Figure 10b), may originate when quasi-recurrent SW structures (i.e., corotating MIRs) are incident on the TS. These structures can change local conditions for ion injection, acceleration, and escape from the TS along upstream field lines. After V1 crossed the TS into the HSH, the intensities in all ion channels first increased, then fluctuated for 20-30 days, and then became relatively steady, remaining essentially flat at lower energies and increasing slowly at higher energies (Figure 10a). At the TS crossing, the intensity of 40-53 keV ions increased tenfold, reached a new peak ≈500, dropped, and thereafter was relatively smooth, varying typically by no more than ≈ 20% about a mean of ≈300 for the next six months.

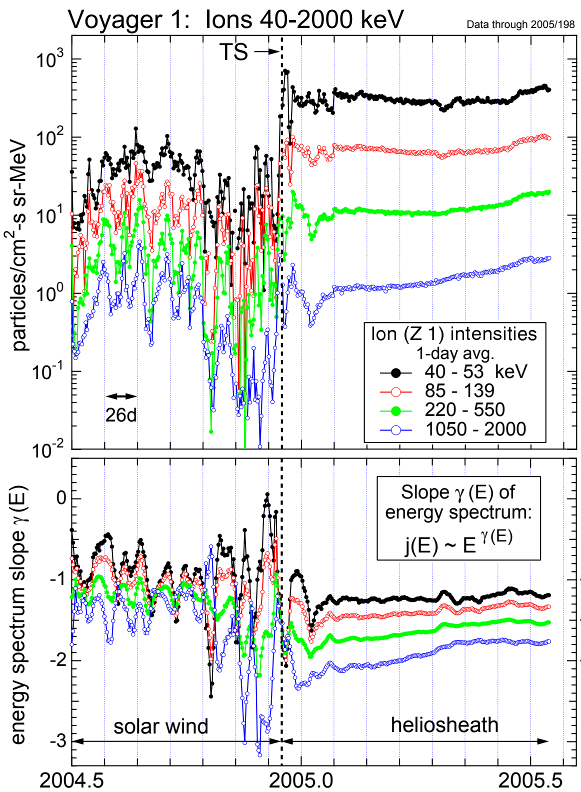

FIGURE 10. (a) intensities and (b) energy spectral indices γ(E) for four of eight low-energy ion channels, 40-4000 keV, from the LECP instrument on V1.

The energy spectrum in the HSH hardens with time; Figure 10b shows that the intensities of the higher energy ions increase while those of the lower energy ions are roughly constant. On 2005.10, the energy spectral index was -1.3 for 40-53 keV ions and -2.2 for 1.05-2.00 MeV ions. By 2005.54, the index was still about -1.3 for 40-53 keV ions, but had decreased to -1.8 for 1.05-2.00 MeV ions. As time progresses, the HSH ion intensities continue to increase faster at higher energies. As of 2005.54, the spectrum from 40-4000 keV is not well fit by a single power-law, but a linear fit yields a mean index of -1.5 ± 0.3. If the low-energy ions were accelerated at the shock by diffusive shock acceleration, then a spectral index of -1.5 ± 0.3 would imply a mean shock strength (plasma density compression ratio) of 2.5, consistent with a compression ratio of near 3 measured by the magnetic field experiment on V1 [*Burlaga et al.*, 2005a].

The angular distributions of ions from 40 keV to at least 30 MeV were highly anisotropic during the 2.5-year approach of V1 to the TS. The angular distributions had unidirectional, beamlike anisotropies with amplitudes ∼0.5 - 1, with the beams directed mainly outward away from the sun in a near-azimuthal direction, i.e., along the -T axis [*Krimigis et al.*, 2003; *Krimigis et al.*, 2004; *Decker et al.*, 2004]. In the HSH the ion anisotropies were much smaller and more variable in direction [*Decker et al.*, 2005; *Krimigis et al.*, 2005]. Figure 11 shows angular data for 53-85 keV ions in the HSH from 2004.96-2005.54. Figures 11 (b) and (c) show that the first 7 whiskers, from the pre- and post-TS intensity spikes, have large +T components. For the next 18 days (2004.97-2005.02), the -T and +R components are large, resembling the beam-like anisotropies observed in the SW prior to the TS crossing. From about 2005.05 to 2005.30, A1/A0 fluctuated over a range of directions and amplitudes; several periods had -R components that persisted several days. During this interval, the radial convective flow speeds fluctuated between -50 and 0 km/s (negative speeds indicate sunward flows), as discussed below in reference to Figure 12. Finally, from about 2005.30 to 2005.54, A1/A0 maintained -T and small +R components, with an amplitude increase (Figure 11d) near 2005.45, which marked a return to sustained positive radial velocity components.

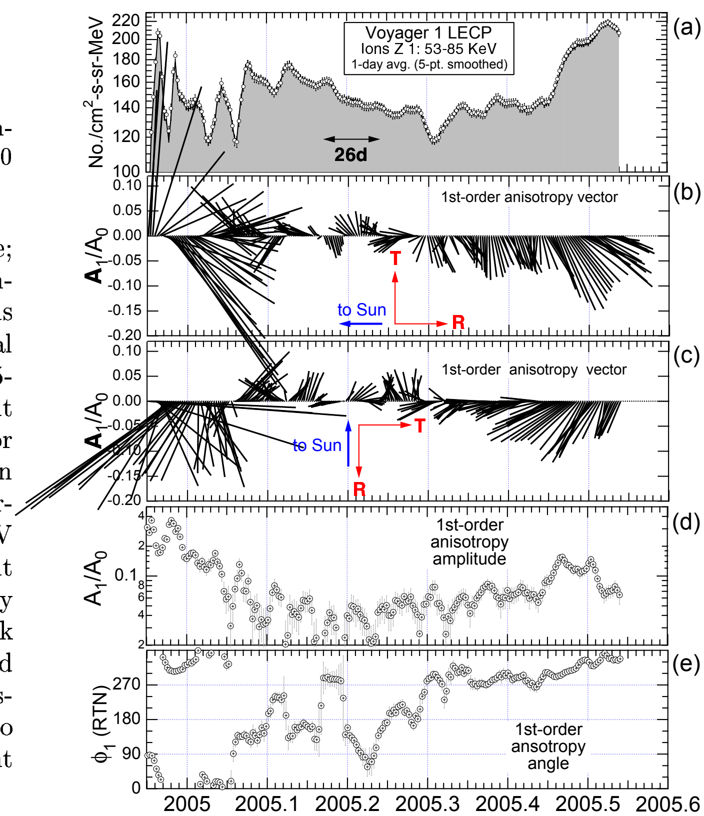

FIGURE 11. Angular data for ions 53-85 keV during the period 2004.96-2005.5.

Flow velocities can be estimated from angular distributions of 40-4000 keV ions when their intensities are sufficiently high. The inset pie plot in Figure 12a shows the LECP scan plane and the viewing directions of the sectors, numbered 1-8, relative to the T- and R-axes. Ions entering sector 1 (S1) have velocities directed nearly anti-sunward (i.e., 22.5° from +R), while those entering S5 have velocities directed nearly sunward (i.e., 22.5° from -R). For each ion channel in panel (a), we show the intensity in S1 (black) and S5 (red), with gray shading denoting S1>S5 (positive radial anisotropy) and red shading denoting S5>S1 (negative radial anisotropy). A non-zero measured radial anisotropy need not imply convection. But a field-aligned anisotropy that has a radial component in the flow frame, for example, is properly handled in the flow extraction algorithm when magnetic field vector data are included. In panels (b) and (c) the MAG vector data are included through 2005.16 (DOY 61). After 2005.16 it was assumed that the field vectors had a +T component only (no N or R components). The estimates of V_R based on data from the two channels (Figure 12a) agree well, especially when the MAG data are used.

Figures 12 (b) and (c) show that 5-6 days after the TS crossing, V1 began measuring a positive radial flow component fluctuating around $V_R \approx +100$ km s^{-1}, which continued for 27-28 days. Near 2005.045, V_R decreased rapidly (within about 5 days) and flow became inward from 2005.063-2005.300. From about 2005.30-2005.4, V_R was 0 to +30 km s^{-1}, although panels (b) and (c) predict different values of V_R. V_R increased again around 2005.45 and remained near +50 to +100 km s^{-1} until at least 2005.54. These excursions of V_R over a period $\approx$ 90-140 days are consistent with V1 sampling the variable flow downstream of an inwardly moving TS. Convective flow at V1 that fluctuates about zero implies that V1 would essentially be riding with and sampling the same parcel of plasma for an extended period.

The intensity of MeV protons in the HSH is much less variable than that upstream of the shock, as shown in Figure 13 [*Stone et al.*, 2005; *Decker et al.*, 2005]. Upstream, the daily-averaged intensities of 0.5-0.7 MeV protons were highly variable with an RMS variation of 47%. Downstream, the RMS day-to-day variation was only 5%. The low variability of the intensities in the HSH indicates that the TSP source is relatively steady and the connection to the source is stable, as expected in the HSH.

The directional intensity of the TSPs is measured by the four low energy telescopes (LETs) on the Cosmic Ray Subsystem (CRS). Telescopes A and B are sensitive to ions streaming outward along the spiral magnetic field in the -T direction, and the telescope C is observing in the opposite direction (see the inset in

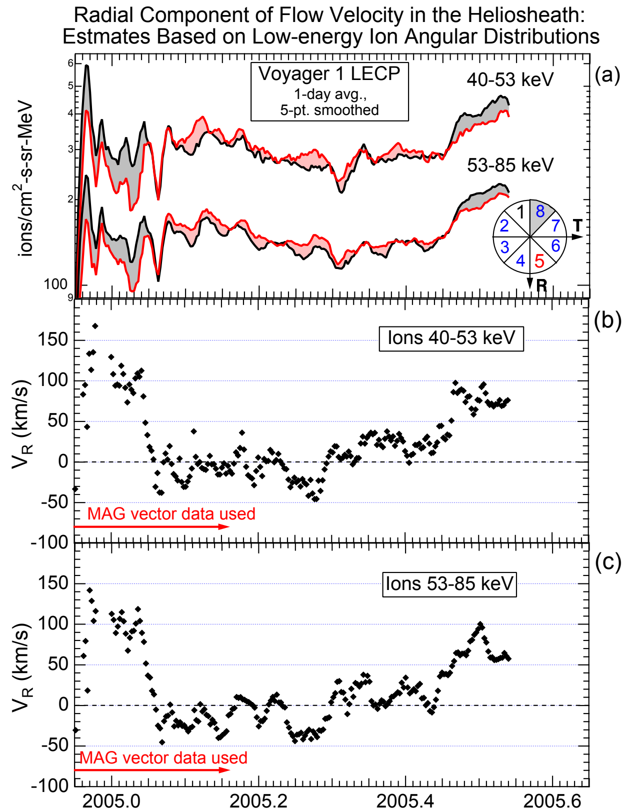

FIGURE 12. (a) Daily averages of 40-53 and 53-85 keV ion intensities. Gray shading denotes S1>S5 (positive radial anisotropy) and red shading denotes S5>S1 (negative radial anisotropy). (b) and (c) show the estimated radial component of the convective flow velocity V_R, based upon application of the velocity extraction algorithm to the full set of angular data from the two ion channels in (a).

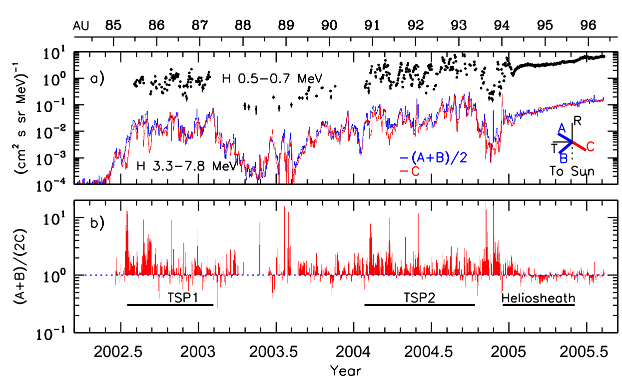

FIGURE 13. (a) Proton intensity observed by CRS particle telescopes A plus B, which are sensitive to ions streaming outward along the spiral magnetic field in the -T direction, and observed by telescope C in the opposite direction. (b) Daily values of the azimuthal streaming amplitude.

Figure 13a). The strength of the field aligned beaming is given by the intensity ratio (A+B)/2C. Upstream of the TS (days 2004/020 to 290), this ratio ranged up to ~10 and had a mean of 1.7 with a daily RMS variation of 1.3. Downstream of the TS, in the HSH, this ratio had a mean of 1 with an RMS variation of only 0.16. The reduced anisotropy in the HSH is expected [*Jokipii and Giacalone*, 2004] because the TSPs undergo more scattering due to the increased magnetic turbulence [*Burlaga et al.*, 2005a].

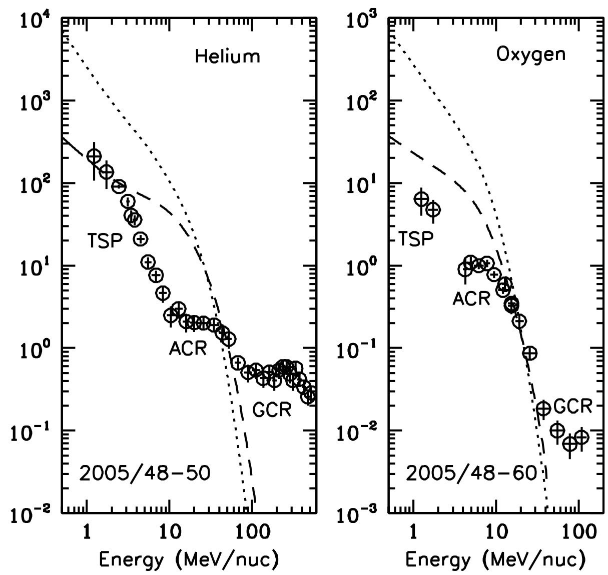

FIGURE 14. Typical spectra observed in the HSH. ACR helium and oxygen dominate at mid-energies, with GCRs at higher energies. The predicted ACR spectra at the shock are shown for a strong (r = 4) and a weak (r = 2.4) shock [*Cummings et al.*, 2002].

Figure 14 shows that the ACR component dominates the He spectrum between 10 and 60 MeV/nuc and that the ACR spectrum is similar to the predicted source spectrum above ~30 MeV/nuc. Before Voyager arrived at the TS, the TS was expected to be the source of the ACRs [*Pesses et al.*, 1981]. Little modulation of the source spectra was expected in the HSH [*Florinski et al.*, 2004]. However, at 20 MeV/nuc the observed intensity is less than one tenth of the predicted source intensity, indicating that substantial modulation of ACRs occurs even in the immediate vicinity of the TS. Figure 14 shows a similar modulation of ACR O; little modulation occurs at E > 10 MeV/nuc, but at 4 MeV/nuc only ~5% of the intensity expected for a weak shock source spectrum is observed. Thus, the recent observations indicate the source of ACRs is not the region of the TS that was crossed by V1.

The 16 MeV/nuc ACR He was strongly modulated at the TS, but its intensity has increased by a factor of 4 since the TS crossing (Figure 15). The increase could be due to a decreasing level of solar modulation, but

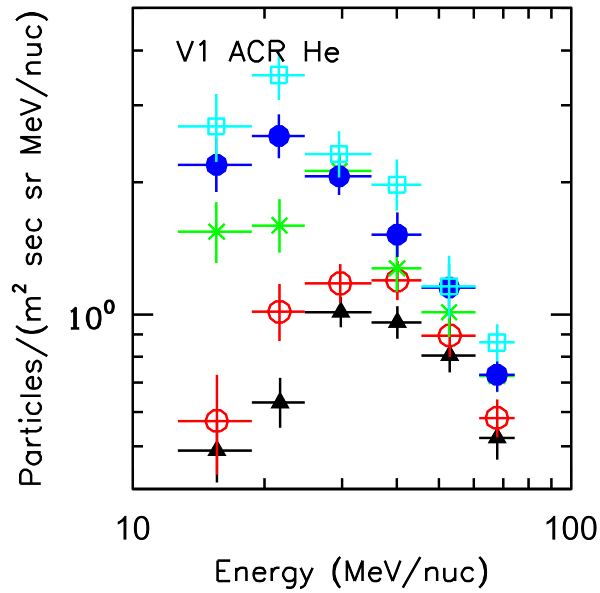

FIGURE 15. ACR helium spectra upstream of the shock (triangles, 2004/313-350) and in the HSH (open circles, 2004/352-2005/52, x, 2005/53-104, solid circles, 2005/105-156, open squares, 2005/157-208).

could also indicate that the 16 MeV/nuc ACR He has a positive radial gradient in this region of the HSH. If the ACR spectrum continues to unroll toward the predicted source spectrum at low energies, the ACR He intensity will eventually exceed the TSP He intensity.

Modulation in the HSH may differ from that in the SSW, because the diffusive mean free path should be shorter and the convective speed much slower and increasingly non-radial farther downstream from the TS. In addition, the waviness of the heliospheric current sheet will be compressed and distorted by the flow of the HSH plasma, affecting the curvature and gradient drifts of the ACRs. As the current sheet tilt decreases to ~10° over the next two to three years with the approach of solar minimum, the change in the particle drifts could be observable by V1 at 35° N.

The relationship between ACRs and TSPs is unknown. Both are deficient in carbon ions, indicating that they are accelerated pickup ions [*Krimigis et al.*, 2003]. However, the H/He ratio is ~10 for TSPs [*Krimigis et al.*, 2003] and ~5 for ACRs [*Cummings et al.*, 2002], suggesting that He is more easily accelerated to ACR energies than H [*Zank et al.*, 2001].

3.2 Magnetic Fields and Plasma in the Heliosheath

The streamlines in the HSH were calculated by *Parker* [1963], assuming subsonic, incompressible, irrotational flow. Using a similar flow model and a kinematic approximation, *Nerney et al.* [1991] and *Washimi and Tanaka* [1996] calculated the variation of the magnetic field B in the HSH. Close to the TS the velocity remains nearly radial and B remains nearly azimuthal. The speed decreases as the plasma moves towards the HP; consequently, the magnetic field strength B increases. *Cranfill* [1971] and *Axford* [1972] showed that if the HSH is thick enough, B might become strong enough to influence the flow. *Nerney et al.* [1993] estimated that B might influence the flow in a restricted region. The flow is deflected away from the radial direction as it approaches the nose of the HP, and B develops a radial component. At the HP, B must be parallel to the surface (unless significant reconnection occurs at the boundary). The observations of B in the HSH from day 352, 2004 to day 110, 2005 show features not described by the simple kinematic models. While B does have a strong azimuthal component, a persistent meridional component is observed that was not predicted [*Burlaga et al.*, 2005a].

The magnetic field direction in the SW is often alternately toward and away from the Sun for several days. The existence of these "sectors" is related to extensions of fields from the polar regions of the Sun to the latitude of the observing spacecraft. Sectors have been observed by V1 out to 94 AU [*Burlaga et al.*, 2003c, 2005a]. One expects sectors and sector boundaries to propagate through the TS. V1 did observe a sector boundary in the HSH that propagated through the TS [*Burlaga et al.*, 2005a]. But it came as a surprise to discover that V1 remained in a positive sector for at least 125 days, as indicated by $\lambda(t)$ in Figure 16B.

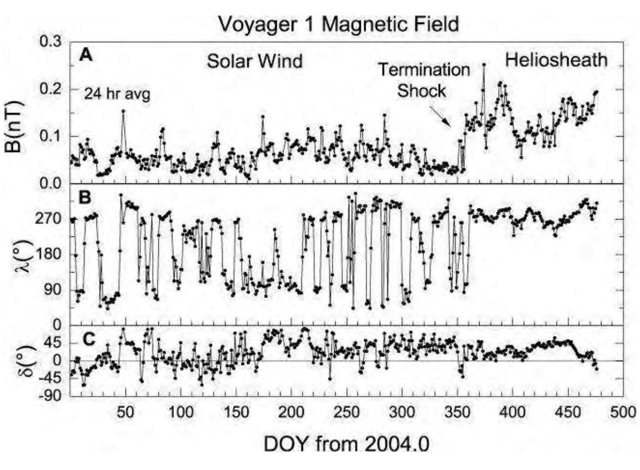

FIGURE 16. The magnetic field strength (A), azimuthal direction (B) and elevation angle (C) measured by V1 before and after the TS crossing.

This observation could be explained if V1 were moving away from the Sun at approximately the same *Jokipii* [2005] calculated that the long duration of the positive sector observed by V1 in the HSH could be due to the reduced speeds behind an inward moving shock. Significant meridional deflection of the HSH flow might also produce long-lasting structures.

The magnetic field and plasma in the HSH which are highly variable on scales from 1 day to several solar rotations are called transient flows. SW transient flows pass through the TS with some modification and new transient flows are generated by either the interactions of SW flows with the TS or by processes in the HSH itself. On the smallest scale, a single forward shock passes through the pickup ion dominated TS; the resulting weakened shock should be observed in the HSH as well as newly created discontinuities and waves [e.g., *Whang and Burlaga*, 1994]. Simulations show that changes in the momentum flux on a scale of several days or more upstream of the TS are sufficient to generate "N-shocks" propagating into the HSH, followed by convected tangential or contact discontinuities [*Zank and Mueller*, 2003]. The momentum flux changes could be produced by ICMEs [*Wang et al.*, 2005; *Richardson et al.*, 2005b], MIRs [*Burlaga*, 1995] and systems of transient flows [*Burlaga et al.*, 2001; *Wang et al.*, 2001a, *Whang et al.*, 2001] that propagate to the distant heliosphere.

Still larger structures (GMIRS), with a scale of tens of AU, have been observed in the SW by Voyager out to 78 AU [*Burlaga et al.*, 2003b]. These GMIRs will also propagate through the TS and into the HSH. Figure 17 shows a model of the disruption of the HSH due to a GMIR propagating across the TS [*Zank and Mueller*, 2003; *Whang and Burlaga*, 1994]. The collision sets up a large-scale, asymmetric ringing of the TS as it oscillates back and forth while gradually damping. A region of heated subsonic SW is produced and convects slowly away from the TS. Finally, the GMIR propagates very slowly into the shocked LISM. The TS relaxes to equilibrium in about 670 days. This scenario is repeated to a greater or lesser extent for every GMIR colliding with the shock. Since the recovery time from the GMIR/TS collision (~670 days) is much longer than the observed time between MIRs at 70 AU (about 90 days), the HSH should be in a continuously disturbed state.

Models with no HCS tilt predict a highly unstable HCS outside the TS, with a narrow jet of high-speed flow, strong warping of the HCS, and movement away from the ecliptic [*Opher et al.*, 2004]. The instability has a characteristic wavelength of tens of AU. Thus the region near the current sheet in the HSH might be unstable and dynamic on the scale of the HSH.

The HSH will be dynamically active on many scales, possibly more active than the supersonic SW. V2 will monitor the upstream SW so that the effect of shocks and MIRs on the HSH can be directly observed and compared to model predictions. Given the modeled

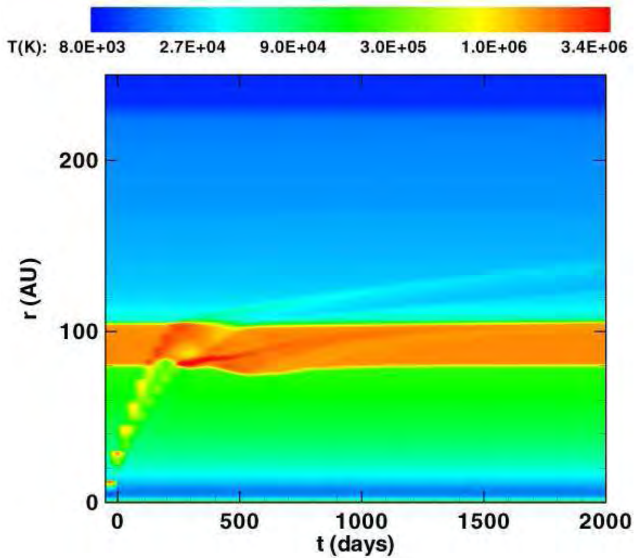

FIGURE 17. Model of the interaction of a GMIR with the TS (from *Zank and Mueller* [2003])

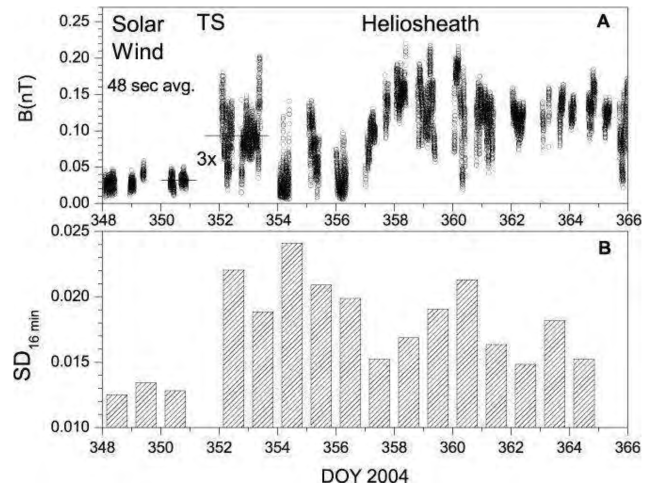

FIGURE 18. A. Fluctuations in 48 sec averages of the magnetic field strength. B. Standard deviations of 16 minute averages of the components of the magnetic field.

thickness of the HSH, Voyager will spend the better part of a solar cycle in the HSH and will be able to study the time evolution of the HSH.

At scales of less than ~1 day, the flow behind the TS in the HSH is expected to be turbulent [e.g., *Zank*, 1999] by analogy with flows behind planetary bow shocks and heliospheric shocks. Figure 18 shows that the spectrum of magnetic field fluctuations behind the TS in the HSH on day 352 does have more power than the fluctuations observed in the heliosphere on day 350, just before the TS crossing on day 351. The spectrum also has a slope consistent with physical turbulence. However, the turbulence behind the shock on scales of several hours is complicated, because a) the gyrofrequency of the pickup ions is within the scales of the spectra, and b) the associated convection time is not accurately known since the speed is not measured directly by V1.

Large-scale fluctuations in B are observed on scales from ~1 day to ~1 year in the SW [*Burlaga*, 1995]. The large-scale fluctuations in the subsonic HSH are different from those in the supersonic SW. For example, *Burlaga et al.* [2005a] reported that the distribution of hour averages B in the HSH is Gaussian (Figure 19), in contrast to the lognormal distributions typically observed in the SSW [*Burlaga*, 1995].

The multi-scale large scale fluctuations in the SSW have a multifractal structure [*Burlaga*, 2004] and can be described by nonextensive statistical mechanics [*Burlaga and Vinas*, 2005a,b]. The appropriate statistical mechanics in the HSH remain to be determined.

Magnetic reconnection is a process by means of which the topology of the magnetic field can change

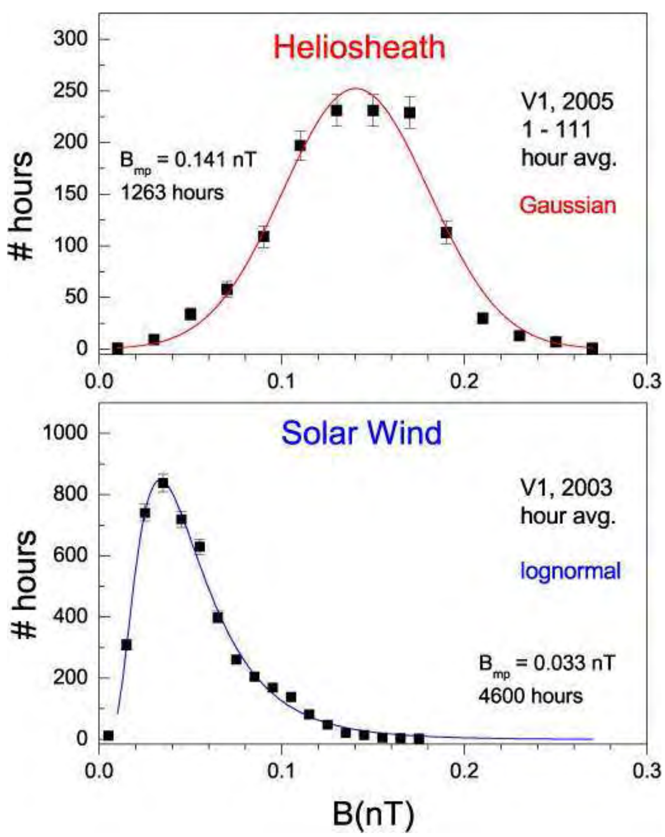

FIGURE 19. The distribution of large-scale fluctuations of B in the SSW is typically lognormal (bottom), whereas the distribution observed in the HSH was found to be Gaussian(top).

and magnetic energy is converted to the energy of flows and energetic particles. Laboratory experiments provide strong evidence for the existence of the magnetic reconnection process. In SW studies, reconnection is often invoked but seldom seem. Solar wind observations are consistent with the existence of very localized reconnection at some points [*Burlaga and Ness*, 1968; *Farrugia et al.*, 2001; *Zurbuchen*, 2002; *Gosling*, 2005a,b]. Nevertheless, there is as yet no direct evidence for a dominant dynamical role of magnetic reconnection in determining heliospheric structure and dynamics. Reconnection could play a major role in the HSH, altering the structure and motions on both large and small scales. *Opher et al.* [2004] proposed a model in which magnetic reconnection occurs at sector boundaries in the HSH behind the TS. *Nerney et al.* [1991] suggested that magnetic reconnection at the HP is "inevitable", as magnetic fields of one sector in the HSH are pressed against the interstellar magnetic fields draped around the HP.

3.3 Future Work

• Determine the source region of the ACRs. One hypothesis is that the source is at lower latitudes than V1, where increased turbulence might result in a higher rate of diffusive shock acceleration. Other possibilities are that the source is at polar latitudes or further out in the HSH.
• Observe the evolution of the ACR spectra as solar minimum conditions are established in order to better understand modulation in the HSH.
• Continue observations of the ACR spectrum with V1 and compare them with observations from V2 as it approaches the shock in the next three to five years. This comparison will provide additional insight into the location of the ACR source and should help determine whether TSPs are the superthermal injection source for the diffusive shock acceleration of ACRs.
• Determine the large-scale magnetic field and flow speed in the HSH along the trajectories of V1 and V2. This result will constrain MHD models of the HSH, which will then give a comprehensive picture of the magnetic fields and flows in the HSH.
• Search for evidence that the magnetic field increases as the HP is approached and the possible effect of this increase on the plasma flow.
• Determine the cause of the "away" fields observed by V1 after crossing the TS, and understand the relation between the TS motion and the structure of sectors and the HCS.
• Study the fluctuations in the HSH that are generated at the TS.
• Study the large-scale fluctuations in B (as well as the plasma parameters which will be measured when V2 enters the HSH) that will be observed throughout the HSH, far from the TS.
• Determine whether the the multiscale large-scale fluctuations in the HSH are organized by nonextensive statistical mechanics (as in the SSW) or by Boltzmann-Gibbs mechanics reflecting a transition to a multiscale equilibrium state.
• Search for evidence of magnetic reconnection in the HSH and near the HP.
• Combine V1 LECP ion angular data and MAG vector data in the flow-extraction algorithm to calculate 3D flow velocity vectors in the HSH; look for meridional flows and for steady rotation of HSH flow velocity toward the heliotail as V1 approaches the HP.
• Search low-energy ion energy spectral and angular data for evidence of reacceleration in the HSH at transmitted SW shocks, at shocks created by SW/TS interactions, and by statistical processes such as 2nd-order Fermi acceleration by MHD enhanced turbulence.

4. THE HELIOPAUSE AND INTERSTELLAR MEDIUM

As the Voyagers begin their trek through the uncharted HSH, the next mile post in their voyage will be the HP. The HP is thought to be a tangential discontinuity with a large jump in the plasma density and a rotation and change in the magnitude of the magnetic field. Given the lack of an operational plasma instrument on V1, observation of the crossing of the HP will probably be identified by a durable change in magnitude and/or direction of the magnetic field.

The V1 flow velocity vectors can be estimated from low-energy ion angular data and are expected to become tangent to the nominal HP surface. However, variations of the HP surface and fluctuations in the flow velocities could make it difficult to use these data to identify a HP crossing. In analogy with planetary magnetopauses, the HP is probably a complex surface that varies locally in thickness and orientation and is the site of patchy reconnection and a variety of plasma instabilities. The appearance of large variations in flow velocities associated with disturbances from such relatively small-scale dynamical processes may indicate that V1 is near the HP. Reconnection at the HP-LISM interface could accelerate low-energy ions (and electrons) and create large departures from the normal HSH intensities and anisotropies. Intermittent reconnection along a slightly corrugated HP surface might appear in the low-energy ion (and possibly, electron) intensity-time profiles as gradual intensity increases with superposed, anisotropic intensity spikes as the spacecraft approached the HP, not un-

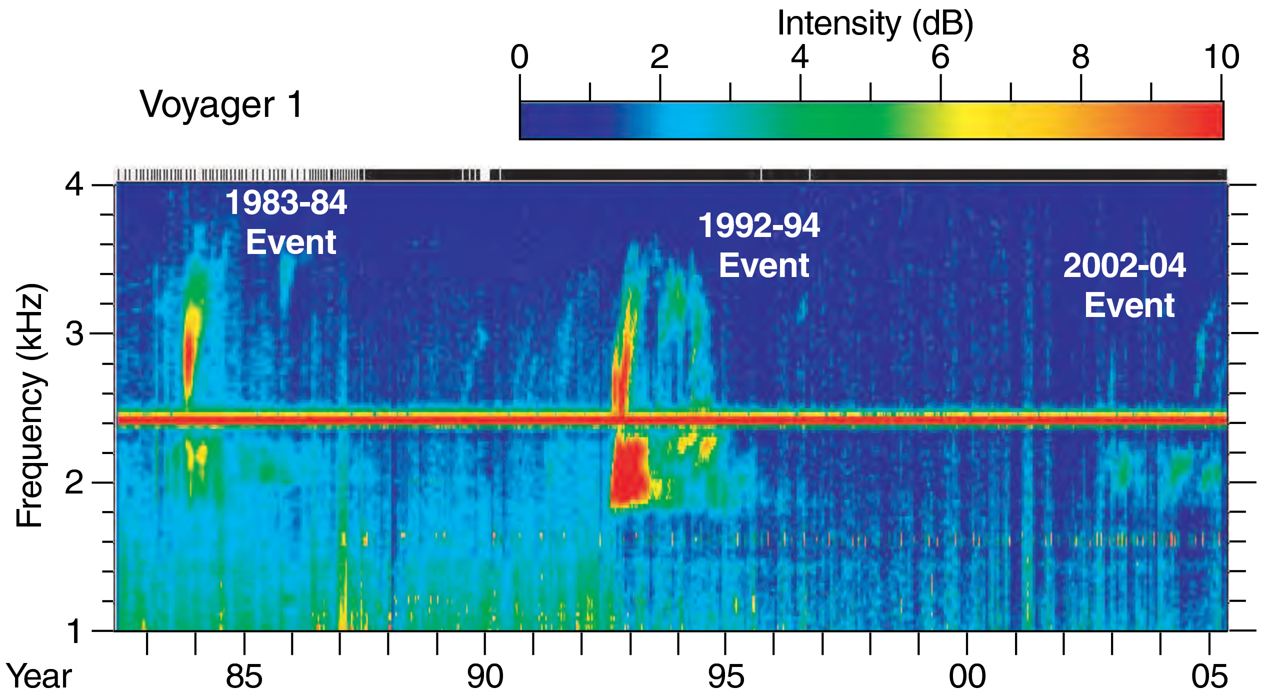

FIGURE 20. Major heliospheric radio emission events.

like structures encountered by V1 as it approached the TS. These comments are speculative, drawing largely upon analogies to planetary magnetopauses; however, as with the TS, energetic particle observations may enable us to remotely sense the HP well before the Voyagers cross it.

Figure 20 shows the low-frequency (1.8-3.6 kHz) radio emissions detected by the Voyager PWS instruments. These emissions are generated at or beyond the HP by transient SW shocks associated with GMIRs interacting with the LISM. The radio waves are generated by a nonlinear interaction of Langmuir waves [*Kurth et al.*, 1984; *Gurnett et al.*, 1993; *Cairns and Zank*, 2003], either with themselves or with low frequency waves. Thus, the appearance of Langmuir waves may be an indicator of entrance into the LISM.

Three major radio emission events have been observed to date, with onsets in 1983, 1992, and 2002 during the declining phases of the last three solar cycles. The radio emission event beginning in 2002 was the first radio activity since mid-1996 [*Gurnett et al.*, 2003]. Figure 20 shows that this emission is weaker than the events of 1983 and 1992. Recent attempts to predict the onset of radio emissions [*Wang et al.*, 2001b; *Zank et al.*, 2001] based on shock arrival times at the HP [*McNutt*, 1988] have failed; hence, many questions remain about how the radio emissions are triggered and generated. With V1 now in the HSH, observations of structures evolving through the subsonic SW may shed light on which structures trigger the heliospheric radio emissions.

Table 1. Model predictions of TS and HP positions for a variety of LISM magnetic field strengths and orientations.

B(μG)	α	V1 TS (AU)	V1 HP (AU)	V2 TS (AU)	V2 HP (AU)
2.4	90°	90	122	90	122
2.4	45°	90	145	76	109
1.5	45°	90	150	83	119
2.5	45°	90	146	87	139

The interstellar magnetic field could result in an asymmetrical distortion of the TS and HP and significantly affect the width of the HSH [see, e.g., *Linde et al.*, 1998; *Ratkiewicz et al.*, 1998; *Pogorelov et al.*, 2004]. The nature of the distortion depends on the orientation and strength of the field. Figure 21 shows that the location of the sources of heliospheric radio emissions lies along a line roughly parallel to the galactic plane; *Kurth and Gurnett* [2003] suggest that the magnetic field may also be parallel to that plane, although details of such a mechanism are not understood. A different field orientation is derived from differences in the flow velocities of interstellar H and He [*Lallement et al.*, 2005 ; *Izmodenov et al.*, 2005].

MHD models of the heliosphere that include the effects of an interstellar magnetic field reveal that the

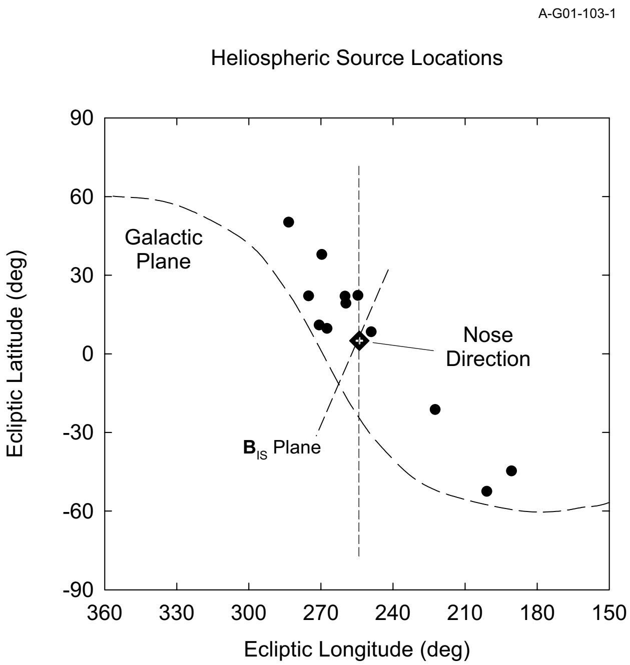

FIGURE 21. Heliospheric radio sources and the orientation of the local interstellar field according to *Lallement et al.*, 2005.

distortion of the heliosphere is sensitive to the angle between the field and the velocity of the interstellar wind. For example, the results of *Pogorelov et al.* [2004] can be scaled to match an average shock location of 90 AU at V1 (35° N) and then used to predict the average shock location at V2 at 30° S and the HP locations for V1 and V2. The results in Table 1 assume that the interstellar B is parallel to the meridional plane through the nose of the heliosphere (vertical dashed line in Figure 21) and makes an angle α with respect to the velocity of the interstellar wind. When the field is perpendicular to the LISM velocity, the asymmetry between V1 and V2 is small. However, if the angle is 45°, the shock and the HP are noticeably closer at the latitude of V2 than at V1. The final line in the table, scaled from an MHD model [*Izmodenov et al.*, 2005] which includes interstellar neutrals and a LISM magnetic field (but no SW magnetic field) parallel to the plane determined by *Lallement et al.* [2005], shows a smaller asymmetry.

Although the models differ and the angle α is unknown, the results suggest that the average shock distance at V2 could be ~10 AU closer than at V1. In addition, the solar cycle variation of the SW dynamic pressure is such that in 2007 the shock should be several AU closer than average, suggesting that V2 might cross the shock in 2007-2008. The models also indicate that the HSH is likely narrower at V2. V1 and 2 observations of the asymmetry of the TS and HSH should make possible improved models and estimates of the distances to the HP.

Instabilities on the HP have been the subject of theoretical conjecture for several years [cf. *Fahr et al.*, 1986; *Florinski et al.*, 2004] . In principle, the Rayleigh-Taylor instability could be important near the nose of the heliosphere where the difference between the flow densities are large. This instability requires an effective "gravity" or destabilizing force. *Liewer et al.* [1996] proposed that coupling between ions and neutrals via charge exchange would produce such a destabilizing force. Near the flanks, away from the nose, the Kelvin-Helmholtz instability is more likely to be important where the shear velocity across the HP is large. Either type of instability would produce motion of the HP superposed on the "breathing" expected to occur due to varying SW pressure. Estimates of the magnitude of the resulting excursions are tens of AU and have periods of the order of 100 years or more [*Liewer et al.*, 1996; *Wang and Belcher*, 1998]. For Voyager, the long periods make it unlikely that such wave motion can be detected, but the additional radial motion from such instabilities, should they exist, increases the uncertainty in the distance to the HP.

While it is by no means assured the Voyagers will survive to the HP, we must look forward to this possibility. This passage would be humankind's first step beyond the heliosphere into interstellar space and the Voyagers would truly become interstellar probes. They will either measure the direction and magnitude of the interstellar magnetic field or set an upper limit on the field of roughly a half of a microgauss. We will be able to assess the extent to which the outer HSH modulates GCRs. We will make the first measurements which expose the extent to which the heliosphere influences the LISM, whether or not turbulence is present in the immediate upstream LISM, and the flux of ACR's leaving the heliosphere. We will measure the low-energy part of the GCR spectrum for the first time. We may observe the source of low-frequency heliospheric radio emissions directly. The measurement of the magnetic field will give us the Alfvén speed, so we will determine whether a bow shock precedes the heliosphere. We may find whether structures propagate through the LISM and, if so, their nature, where they come from, and what they tell us about the evolution of the interstellar medium and its interaction with astrospheres of stars.

4.3 Future work

- Observe the next episode of the heliospheric radio emissions and try to correlate structure in the emis-

sions with SW conditions.
• Observe the properties of cosmic rays beyond the heliosphere.
• Characterize the HP and LISM and how they are affected by the heliosphere.

5. ENERGETIC NEUTRAL ATOMS

During the upcoming years, while V1 and V2 are providing irreplaceable in situ measurements of the TS and the inner portion of the HSH, they will stimulate an intense theoretical discussion of the global configuration of these regions. Fortunately, a new NASA mission will add unique diagnostic measurements to this scientific adventure. All-sky energetic neutral atom (ENA) images of the global structure of the TS and HSH will be accumulated every half year after launch of the Interstellar Boundary Explorer (IBEX) into a highly eccentric Earth orbit in June 2008 (see the general description of the mission in *McComas et al.* [2004]). These ENAs are generated by charge-exchange collisions between the very slow (26 km/s) inflowing interstellar neutral gas and the protons that are heated/accelerated at the TS and that subsequently populate the entire HSH. Two IBEX single-pixel telescopes will image these hydrogen ENAs over semi-annually precessing great circles in the sky at low energies (10 eV to 2 keV) and in an over-lapping band of higher energies (300 keV to 6 keV). The intensities of the ENAs depend strongly on both the shape of the proton spectrum and the plasma convection flow pattern in the HSH. Where the anti-Sunward component of the HSH convection velocity is high, the ENA intensity directed towards Earth is low, and vice versa. The ENA foreground from the heliosphere between the Earth and the TS is negligible because the solar wind and pickup ion population is being convected away from the Sun at the solar wind velocity (which is greater than the Earth-directed velocities of the thermal or pickup ions). Beyond the TS, the shocked decelerated flow in the HSH allows heated/accelerated protons to reach Earth and be imaged by IBEX.

ENA emission as seen from Earth is accumulated along the entire line of sight (LOS) outward through the inner HSH, across the HP and into the outer HSH. The measured ENA intensity integrates the effect of the TS heating/acceleration and HSH plasma flow over several tens of AU, thus yielding diagnostics of this immense boundary region (Gruntman et al., 2001). Even though V1 and V2 do not directly measure protons in the energy range corresponding to the IBEX ENA hydrogen, these complementary measurements will prove of inestimable value in constraining the theoretical models of the global interaction of the solar wind with the interstellar medium. For example, *Gloeckler et al.* [2005] extrapolated the V1 LECP proton spectra (40-4000 keV) upstream and downstream of the TS (see Fig. 4) to lower energies and demonstrated that 80% of the upstream ram pressure goes into heating the pickup protons (see Fig. 7). Thus V1 provides the input proton spectrum for the global HSH (albeit only at the V1 location) that will be imaged in IBEX hydrogen ENAs. And, returning the scientific favor, the very first IBEX half-year images will, at a glance, reveal asymmetries in the large-scale HSH configuration that bear on the puzzling directions of the magnetic field and energetic particle streaming observed by V1 and V2.

6. VOYAGER COSMIC RAY MODULATION STUDIES

Figure 22 shows the long-term modulation of GCRs and ACRs in the distant heliosphere over solar cycle 23. Several features of these data and of the energetic particle populations observed by V1 at the TS were markedly different from those expected. At 1 AU, the cycle 23 intensity of 265 MeV/n He from solar minimum to solar maximum is reduced by a factor of 4.36, very close to that of cycle 21. At V2 (64 AU) this reduction was 30% and at V1 (81 AU) it was 18% [*Webber and Lockwood*, 2004; *Van Allen and Randall*, 2005 *McDonald et al.*, 2005]. The 11-year solar cycle modulation in the outer heliosphere is very weak.

The effects of the 11-year solar modulation do not extend significantly beyond the TS in cycle 23, which is probably the same as in cycle 21 (i.e., the GCR HSH modulation does not change significantly over this period). The extrapolation of the solar minimum/solar maxima data from successive qA>0 (Sun's dipole points northward) epochs intersect at 88 $\pm$ 4 AU, close to the 94 AU TS location at the December 2004 crossing. The GCR He intensity at the TS over the 1998-2000 period is a factor of 3 below that expected in the local interstellar spectra [*Webber and Lockwood*, 2001], so the HSH plays a significant if not dominant role in the modulation process.

Following the reversal of the Sun's magnetic field in 2000, the 1 AU GCR He intensity is relatively flat from 2001.5-2003.83, followed by a significant recovery immediately after the large solar events of late October and early November 2003. Despite the factor of 16 difference in the depth of the modulation, the relative form of the intensity changes at V2 in the distant heliosphere are similar to those observed at 1 AU. The ongoing recovery of cycle 23 is important for interpreting the Voyager observations near the TS. At V1, 17 AU beyond V2, the GCR and ACR intensity changes

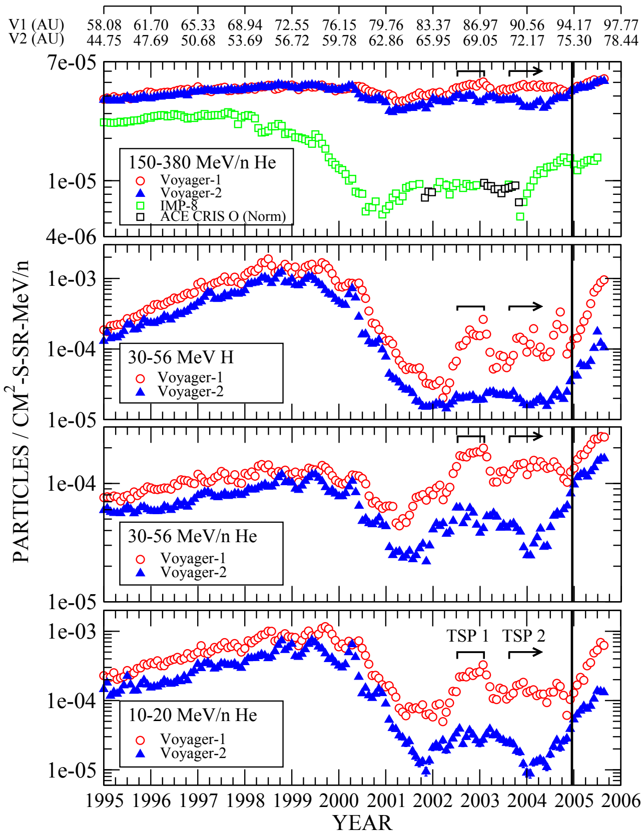

FIGURE 22. 26-day averages of GCR and ACR modulation in solar cycle 23. The vertical black line shows the TS location.

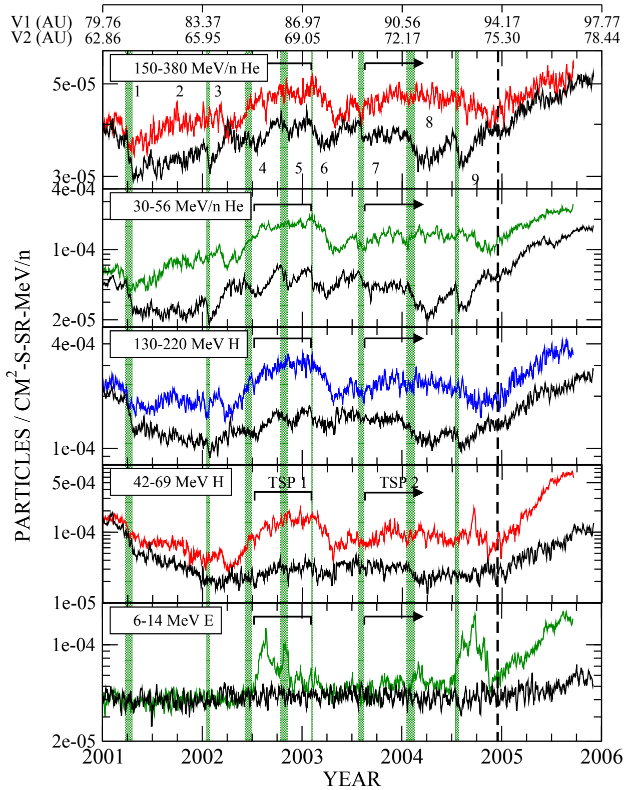

FIGURE 23. 5-day averages of GCR, ACR, and TSP intensities from 2001 to the present. V1 data are shown by colored lines. V2 data (black lines) are time-shifted forward 0.2 years. The vertical dashed line shows the TS location.

are significantly different. These differences are associated with the appearance of the TSP events at V1 which were discussed in detail in earlier sections.

Among the distinctive features of these TSP events are the associated increases of higher energy ions (30-69 MeV H), relativistic 1-15 MeV electrons and their strong modulation by transient disturbances moving out in the interplanetary medium. These TSPs are observed when there is a good magnetic connection between V1 and the TS shock.

In December 2004 V1 crossed the TS and entered the HSH where it has remained for the past 6 months. The Voyager 1 GCR and ACR observations were quite different not only from what was expected but also from what was observed earlier in the TSP events at energies above several MeV/n. Figure 23 shows that just before the TS crossing, the ACR H and He and 10 MeV electron intensities were at a low level. However, a steady and substantial increase in all V1 ACR and GCR ions and electrons began in 2004.88, 30 days before the TS crossing. This increase continues with the cycle 23 recovery as V1 moves deeper into the HSH.

The radial intensity gradients for GCR He and H between 1 AU and V2 from 1997-2005.5 are well behaved and peak at about the time the Bastille Day MIR reaches the TS. The Voyager 1 and 2 265 MeV/n GCR He gradients are fairly constant over the extended solar minimum period and decrease as the recovery from solar maximum conditions begins and with the approach to and crossing of the TS. However, the 130-220 MeV H and 30-56 MeV/n ACR He gradients after 2001 are much larger than expected and show significant structure, suggesting that these higher energy components are related to the TSP events. Contrary to expectations, the GCR and ACR gradients decrease as the TS is approached.

6.1 Cosmic Ray Electrons

The cosmic ray electrons are the most enigmatic of all of the cosmic ray components. The best estimate of the electron LISM spectrum is derived from the low frequency galactic radio spectrum observed at Earth. This radio spectrum directly provides the electron spectrum down to 100-200 MeV through the synchrotron radiation of these electrons in the galactic magnetic fields, the low energy electron limit being determined by free-free absorption in the LISM. The spectrum of electrons is preserved in the radio spectrum, but the intensity of the LISM electrons requires an estimate of the average galactic B field.

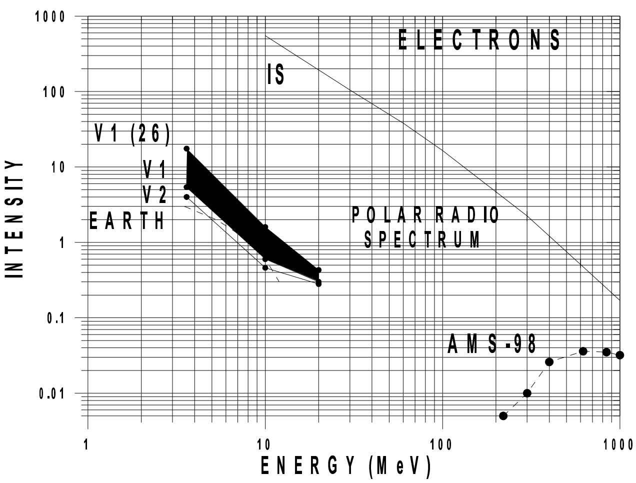

FIGURE 24. The intensity of cosmic ray electrons versus energy.

Figure 24 shows the estimates of the low energy LISM electron spectrum made using the best estimates of the LISM B field along with the low frequency radio spectrum. Also shown is an estimated galactic electron spectrum based on an LISM propagation model with a source spectrum S = -2.3, similar to that used for GCR nuclei. The direct observational data on electrons is summarized at higher energies by the Alpha Magnetic Spectrometer (AMS) data at a time of minimum modulation in 1998. In this energy regime, the modulation of electrons and nuclei are consistent with each other and the modulation models. These models predict a reduction of the LISM intensity by a factor of about 5 at 1 GeV; this reduction increases rapidly at lower energies. In spite of many attempts, the very low electron intensity in the intermediate energy range from roughly 30 to 200 MeV has not been accurately measured. At lower energies, the electron intensities increase rapidly with an E^{-2} spectrum and with much smaller 11-year time variations. This lowest energy component is now believed to consist of both a low energy galactic component and a Jovian component. The Jovian component dominates in the inner heliosphere but decreases with increasing distance from the Sun so that in the outer heliosphere the galactic component dominates.

The overall intensity of electrons remains about the same at the Earth as at 70-80 AU. This intensity is several hundred times less than the expected LISM electron intensity at these energies. The lack of a large radial intensity gradient and the large modulation between the estimated LISM electron intensities and those observed just inside the TS are not predicted by any of the current solar modulation models, despite the success these models have had in explaining the higher energy modulation. The new V1 measurements of a steadily increasing electron intensity beyond the TS, as illustrated by the bottom panel of Figure 23 and the shaded region of Figure 24, may be the first break in this impasse. The next few years, as V1 penetrates deeper into the HSH, will be crucial for understanding this long standing problem and will make an important contribution to the interface between solar system physics and the basic astrophysics of the interstellar medium.

In a recent review of magnetic fields in the Universe, *Vallee* [2004] commented that the single most important new measurement needed to understand these magnetic fields was a direct measurement of B in the LISM. The measurement of the low energy electron spectrum as it evolves in the HSH is of comparable importance. This spectrum, used in conjunction with the low frequency radio spectrum, will give a self-consistent (direct) determination of many parameters related to the LISM and would be a major contribution to galactic astronomy as well as to the physics of the HSH as it leads to the modulation/acceleration of cosmic ray electrons and other particles.

6.2 Modulation Summary

GCR Modulation: The steady increase of the intensity of GCR H and He as V1 moves beyond the TS is a clear indication that solar modulation effects on GCR extend beyond the TS, e.g., the intensities did not immediately jump up to their projected LISM values. This observation is an important constraint for modulation theories which have been ambiguous on that point.

Electron Modulation: The continuing steady electron intensity increase since the TS crossing is the first significant modulation effect seen for 10 MeV electrons. It could be an indication of an extended modulation region of these particles in the HSH (see below) or it could be a temporal effect. This feature has not been considered in most modulation models.

ACR Modulation: The continued increase of ACR intensities beyond the TS was not anticipated by models of ACR acceleration or propagation. The acceleration could occur at different latitudes along the TS shock than measured at V1 or it could be an indication of a large time variability of the ACR intensity at or near the TS shock. The continuing increase now that V1 is at least 2-3 AU beyond the shock could also suggest that the acceleration region is not at the TS but further out, which would require a major modification of ACR acceleration and transport theories.

Future Tasks

- Observe the on-going recovery toward the cycle 23 solar minimum (2007-2008 at V2) and its effect on the V1 and V2 GCRs and ACRs.
- Study cosmic ray modulation in the HSH.
- Provide the first measurements of low energy GCR electrons in the heliosphere.
- Improve the estimates of the LISM GCR spectra.

7. SUMMARY

The Voyager spacecraft continue outward on a mission which is currently encountering truly new heliospheric and extraheliospheric features and has an exemplary record of current scientific productivity. The first encounter with the TS has just occurred and the V2 encounter(s) are probably only a few years distant. Still to come are the traversal of the HSH, the first crossing(s) of the HP, and the first in situ observations of the interstellar medium, which will be spectacular milestones in the exploration of our Sun's surroundings. These encounters could answer many basic, long-standing questions about the plasma and magnetic properties of the LISM, the nature of the TS and its role in the acceleration of the ACRs, the role of the HSH in GCR modulation, the spectra of low energy interstellar GCRs, and the source and location of the heliospheric radio emissions.

Exploratory missions such as Voyager provide key tests of physical theories and also provide observational surprises which often lead to major advances in physical understanding. The energetic particle beams observed upstream of the TS are certainly an example of such a surprise which has revised current thinking on the morphology of the TS surface. The continued ACR modulation in the HSH and increase in 6-14 MeV galactic electrons in the HSH are other examples forcing at least revisions to long-term hypotheses on the acceleration mechanism for these particles. But we have learned to expect surprises from the Voyagers - more are awaited!

The longevity of the Voyagers makes them ideal platforms for studying long-term SW and now HSH variations. Their distance make them ideal for studying the evolution of the SW, shocks, and cosmic rays. The interpretation of Voyager data is greatly enhanced by the ability to compare with data from Earth-orbiting spacecraft (IMP 8, Wind, ACE, SAMPEX), Ulysses, Pioneers 10 and 11 and in the future IBEX. These data make deconvolution of solar cycle, distance, and latitude effects possible. To further this intercomparison of data sets and to provide opportunity for the community to provide new insight into these observations, we strongly endorse Guest Investigator and Theory programs focusing on the outer heliosphere. Theory and multi-spacecraft comparisons are needed to provide the best understanding of the data Voyager provides.

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TECHNICAL/BUDGET

Introduction

Since 1989, after completion of its primary mission of planetary exploration, the Voyagers have been characterizing the interplanetary medium beyond Neptune while they search for the transition region between the interplanetary and interstellar media. Passage through the termination shock by Voyager 1 in December 2004 began the journey through the transition region, the heliosheath and the race toward interstellar space. At the start of the Voyager Interstellar Mission (VIM), the two Voyager spacecraft had already been in flight for over twelve years, having successfully returned a wealth of scientific information about the giant gaseous planets and the interplanetary medium between Earth and Neptune. The Voyagers have now begun their 29th year of flight operations.

Voyager 1 is escaping the solar system at a speed of about 3.6 AU per year while Voyager 2 is leaving at about 3.3 AU per year. Power is the limiting lifetime consumable. The two spacecraft have power to continue returning science data until around the year 2020. It is likely that at least one of the spacecraft could enter interstellar space while adequate power is still available. All other consumables are adequate for continued operations well past 2020.

The Voyager Spacecraft

Voyager spacecraft subsystems and instruments required for the interstellar mission are operating well and are fully capable of supporting the science mission through at least 2020. Although both spacecraft are operating on some redundant hardware, with careful monitoring of spacecraft health, considerable functional flexibility still exists to operate a long duration mission.

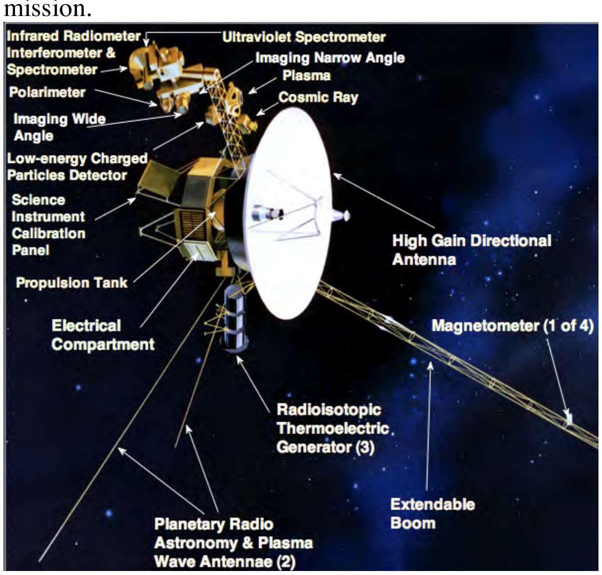

Figure 24: The Voyager Spacecraft

The identical Voyager spacecraft (Figure 24) are three-axis stabilized systems that use celestial or gyro referenced attitude control to maintain pointing of the high-gain antennas toward Earth. The prime mission science payload consisted of 10 instruments (11 investigations including radio science). Only five investigator teams are still funded, though data are collected for two additional instruments, the Planetary Radio Astronomy (PRA) instrument and the Ultraviolet Spectrometer (UVS). Active teams and the status of their instruments are described in Table 2.

Investigator Teams	**Principal*** and Co-Investigators	Instrument Status
Plasma Science (PLS)	**J.D. Richardson*** J. W. Belcher L.F. Burlaga A.J. Lazarus R. McNutt E.C. Sittler, Jr. C. Wang	Instrument performing normally on Voyager 2. Voyager 1 instrument is powered, but ion data not useable
Low-Energy Charged Particles (LECP)	**S.M. Krimigis*** T.P. Armstrong R.B. Decker G. Gloeckler D.C. Hamilton L.J. Lanzerotti B.H. Mauk R. McNutt E.C. Roelof	Instruments performing normally on both spacecraft
Cosmic Ray Sub-system (CRS)	**E.C. Stone*** A.C. Cummings N. Lal F.B. McDonald W.R. Webber	Except for one of four low-energy telescopes on Voyager 2, instruments performing normally on both spacecraft
Magnetometer (MAG)	**N.F. Ness*** M. Acuña L.F. Burlaga J.P. Connerney R.P. Lepping C. Smith F.M. Neubauer	Instruments performing normally on both spacecraft
Plasma Wave Subsystem (PWS)	**D.A. Gurnett*** W.S. Kurth	Voyager 1 instrument performing normally. Voyager 2 high rate data are no longer useable, but low rate data are normal.

Table 2: Voyager Investigations and Status

The entire Voyager 2 scan platform, including all of the platform instruments, was powered down in 1998. All platform instruments on Voyager 1, except UVS, have been powered down. The Voyager 1 scan platform was scheduled to go off-line in late 2000, but has been left on at the request of the UVS investigator (with the concurrence of the Science Steering Group) to investigate excess in UV from the upwind direction. The PLS experiment on Voyager 1 which had been turned off in 2000 to provide power to extend UVS lifetime, was turned on again in 2004 when there was evidence that the spacecraft was in the vicinity of the termination shock. UVS data are still captured, but scans are longer possible.

The Flight Data Subsystem (FDS) and an 8-track digital tape recorder (DTR) provide data handling functions. The FDS configures each instrument and controls instrument operations. It also collects engineering and science data and formats the data for transmission. The DTR is used to record high-rate PWS data, which are played back about four times per year on Voyager 1. However, the high rate PWS data on Voyager 2 is no longer useable, and no special effort is made to capture its playbacks.

The Computer Command Subsystem (CCS) provides sequencing and control functions. The CCS contains fixed routines such as command decoding and fault detection and corrective routines, antenna pointing information, and spacecraft sequencing information. The CCS on both spacecraft are performing normally.

The Attitude and Articulation Control Subsystem (AACS) controls spacecraft orientation, maintains the pointing of the high gain antenna towards Earth, and controls attitude maneuvers. A necessary switch of AACS circuitry was made in 2002 and since then the redundant celestial sensors have been used. Following the switch, the new Canopus Star Tracker (CST) has been losing sensitivity at a higher rate than expected. Based on past experience, it is expected that the sensitivity loss will decrease within the next year or two. The CST has no problem maintaining lock on the reference star or reacquiring after maneuvers.

Uplink communication is via S-band (16-bits/sec command rate) while an X-band transmitter provides downlink telemetry at 160 bits/sec normally and 1.4 kbps for playback of high-rate plasma wave data. Receiver 1 on Voyager 2 failed in 1978. Failure of the Tracking Loop Capacitor in Receiver 2 resulted in a drastic reduction in the acquisition frequency bandwidth, requiring the routine use of special procedures to determine the best lock frequency. Voyager 2 is currently operating on the alternate transmitter following an autonomous switch in 1998. The project has elected to remain on the currently selected transmitter. Telecommunications with both spacecraft are normal and the link margins are sufficient to maintain two-way contact with the spacecraft well after 2020.

Electrical power is supplied by three Radioisotope Thermoelectric Generators (RTGs) that are performing nominally. The current power levels are about 295 watts, with power margins of about 35 watts and an average degradation rate of about 4.4 watts per year. As the electrical power decreases, power loads on the spacecraft will have to be turned off, reducing spacecraft capabilities and operational flexibility. Power margins are adequate to operate a complement of science instruments until about 2020.

Spacecraft attitude is maintained by small hydrazine thrusters. One thruster has failed on Voyager 2 and one on Voyager 1 has shown signs of significant degradation, due to exceeding expected end-of-life usage. The thrusters currently in use are expected to last the rest of any mission projection. Nearly 1/3 of the original propellant remains available.

Operations Concept

The VIM is characterized by (1) science requirements that can be satisfied with science instrument observations that are primarily repetitive in nature, and (2) long (and increasing) communication distances. The resulting long round-trip-light-times and decreasing signal levels significantly constrain spacecraft monitoring and control.

Programmatic changes since the beginning of the VIM have significantly reduced flight team staffing levels. As opposed to the multiple teams of specialists earlier in the mission, each member of the current flight team performs multiple interdisciplinary functions and only limited backup capability exists.

These mission characteristics and the small team size have resulted in the evolution to the current methods used to conduct mission operations. Multi-mission ground data systems are used, though Voyager requires some unique components to maintain compatibility with the multi-mission environment. Dramatic changes have been made to the process for real-time monitoring of routine spacecraft operations. Each of these is discussed further in the following sections.

The mission impact of the reduced staffing includes reduced operational flexibility, greatly reduced anomaly response capability, and potential delays in science data delivery. In addition, many important but non-essential tasks are not being performed.

Sequence Generation

Key to acquiring the desired science observations and maintaining an adequate level of mission adaptivity is the sequencing strategy. Because of the limited flight team resources available for spacecraft sequence generation, this strategy minimizes the labor required while satisfying the science data acquisition requirements and flight system health and safety engineering needs.

Voyager's process of command sequence generation, review and uplink is unique to this mission. It requires continual support by Voyager-experienced personnel.

The sequencing strategy is composed of four basic elements. First is a continuously executing sequence of repetitive science observations and engineering calibrations called the "baseline sequence." A baseline sequence is stored on-board each spacecraft and contains the instructions needed to acquire and return the basic science data to the ground. This sequence will continue to execute for the duration of the mission, but requires periodic adjustment to deal with changes in spacecraft health and configuration, ground system capabilities and the heliospheric environment.

The second element is the storage on-board each spacecraft of the pointing information necessary to keep the boresight of the High Gain Antenna (HGA) pointed at the Earth. This provides the capability for continuous communication with each spacecraft without further HGA pointing commands. HGA Pointing Tables will require updating on both spacecraft within the next few years to maintain an acceptable pointing accuracy needed for quality science data acquisition. Special skills are needed for this task, as discussed below.

The third element provides the capability of augmenting the baseline sequence with non-repetitive science or engineering events using either an "overlay sequence," or a "mini-sequence." The difference between these two types of augmentation sequences is that the overlay sequence operates for a fixed interval of time, currently 3 months, and contains all of the baseline sequence augmentations for that time interval. A mini-sequence is focused on accomplishing a single augmentation need and is not a regularly scheduled activity but is done on an as-needed basis.

The fourth element is the use of pre-defined and validated blocks of commands (high level sequencing language), rather than the optimized sequence of individual commands (low level sequencing language) used during the prime mission, to accomplish desired spacecraft functions. The use of pre-defined blocks of commands greatly reduces the effort required to generate and validate a sequence of commands. The spacecraft contains pre-defined blocks of commands to support this functionality for routine activities.

Transmitting the Data to the Ground

The Voyager Interstellar Mission is, with one exception, a real-time data acquisition and return mission. All of the operating instruments on each spacecraft are continuously collecting data for immediate transmission to Earth. The normal real-time transmission data rate is 160 bits per second (bps), including 10 bps engineering data

The one exception to real time data return is that once a week, 48 seconds of high rate (115.2 kbps) plasma wave data are recorded onto the DTR. Currently, a second 48 seconds per week is recorded on Voyager 1. These data are played back every 6 months and provide increased spectral resolution snapshots of the plasma wave information. These high rate plasma wave data have provided the primary data for the Plasma Wave Investigation Team's estimate of the termination shock and heliopause locations. The corresponding data on Voyager 2 are not usable. Recording and playback of Voyager 1 high rate plasma wave data can continue until the years 2010 when telecommunications capability will no longer support the playback data rate of 1.4 kbps.

Capturing the Data on the Ground

Real-time telemetry data capture is accomplished using 34- and 70-meter tracking antennas of the DSN. Capture of the recorded high rate plasma wave data from Voyager 1 requires the use of an array of 70- and 34-meter antennas.

Sixteen hours per day of tracking support for each spacecraft is the project's target for science data acquisition, particularly in the vicinity of the termination shock. Because Voyager is not a high priority mission, it is usually allocated support after higher priority mission requirements have been satisfied. In the recent past, the average daily support has been about 8-12 hours. Future increases in missions being supported by the DSN will result in reduced tracking station availability for Voyager. As tracking support is reduced, the ability to characterize the heliospheric medium is degraded. Acceptable minimum science data acquisition requirements range from 4 to 12 hours per day per spacecraft, depending on the specific investigation.

Delivery to Science Investigation Teams

Science data are provided electronically to the science investigation teams in the form of a Quick Look Experiment Data Record (QEDR) and Experiment Data Record (EDR). Voyager 1 and Voyager 2 QEDRs for each science investigation are generated daily (Monday through Friday) containing the available data since the last QEDR was produced. Since these products are produced in near real-time, generally within 24 hours of the data capture, data gaps due to a variety of ground system problems can be present in the QEDR. Once a week, EDRs are created for the previous week's data. In this product, data gaps resulting from ground problems have been filled to the extent possible. When the final EDRs are available, science teams are notified by electronic mail. The science teams then retrieve the data at their convenience for further processing and analysis.

Spacecraft Monitor and Control

Spacecraft monitor and control includes the real-time functions necessary to monitor spacecraft health and to transmit and verify commands to insure data capture during special activities, and support non-realtime functions. With the reduced flight team staffing during VIM and the acceptability of increased risk during an extended mission, real-time support is limited to weekday prime shift and special off-shift events (commanding, DTR playbacks, and attitude maneuvers). This reduced real-time monitoring support was enabled by the development and implementation by Voyager personnel of an automated telemetry monitoring tool which alerts on-call personnel to potential anomalous spacecraft conditions. This automation tool, Voyager Alarm Monitor Processor Including Remote Examination (VAMPIRE), has served as a model for development of a similar multi-mission tool now in use by other missions.

Maintaining spacecraft health and safety is a non-real-time function. It includes: the analysis of engineering telemetry data to establish and evaluate subsystem performance trends; the periodic in-flight execution and analysis of subsystem calibrations and engineering tests; analysis of AACS, FDS, and CCS memory readouts; the review and updating of telemetry alarm limits; the identification and analysis of anomalous conditions; and the implementation of corrective actions. Detailed anomaly analysis has suffered recently because of the level of staffing.

The analysis of engineering telemetry data to establish and evaluate subsystem performance trends is an important operations function. It drives decisions about future optimum configurations for maximizing mission lifetime. The analysis of these data relies on the system and subsystem expertise retained by the individual flight team members. Like anomaly analysis, as the flight team loses subsystem expertise due to the retirement of experienced personnel and the downsizing of the flight team, the ability to perform trend analysis is severely impacted. Development of an automated process for trend data gathering and display is considered a crucial future development to improve operations efficiency.

Periodic in-flight calibrations and engineering tests are used for verifying spacecraft performance, analyzing anomalies, and maintaining spacecraft capabilities. While some of these calibrations and tests are included in the baseline sequence, the majority are initiated from the ground in either an overlay or mini-sequence.

The identification and analysis of anomalous conditions and the determination of recommended corrective actions relies on the system and subsystem expertise of the individual flight team members. An automated tool, Monitor/Analyzer of Real-time Voyager Engineering Link (MARVEL) monitors CCS/FDS telemetry data to assist the analyst with normal event verification and to display on a workstation screen any conditions that are not as predicted. MARVEL performs limited analysis of the CCS/FDS telemetry and identifies possible causes of the anomalous condition and potential corrective actions from the stored knowledge base within the program.

Protection Against Spacecraft Failures

In order to maximize the spacecraft science data return reliability for a mission that could potentially continue until 2020 or beyond, automated safeguards against possible mission-catastrophic failures are provided.

Each spacecraft has Fault Protection Algorithms (FPAs) stored on-board that are designed to recover the spacecraft from otherwise mission-catastrophic failures. The FPAs are mostly implemented in the CCS while a few are interactive with the AACS. The five FPAs stored in the CCS execute pre-programmed recoveries for the following:

- AACS anomalies
- Loss of command reception capability
- Exciter and transmitter hardware anomalies
- CCS hardware and software anomalies
- Anomalous power loads

In addition, there are fault correction routines in the AACS to deal with failures of its specific circuits and sensors.

The second safeguard is the Backup Mission Load (BML), which provides automated on-board protection against the loss of command reception capability. Without command reception capability, the spacecraft must continue to operate with the instructions previously stored in the CCS memory. The BML reconfigures the spacecraft for maximum telecommunications and attitude control reliability and modifies the Baseline Load to continue the acquisition and transmission of fields, particles and waves science data as long as the spacecraft continues to function.

All of the above protection mechanisms require periodic review and occasional modifications by the Flight Team. These are dictated by unpredictable changing conditions.

Consumables Management

Both spacecraft have on-board consumables that are adequate to support spacecraft operation until at least 2020. Electrical power is clearly the major spacecraft lifetime limiting consumable. Power should be adequate to support at least some science data acquisition until at least 2020. Both spacecraft have about 30 kg of hydrazine that provides a minimum of about 50 years of operation at current usage rates.

Mission Adaptivity

While Voyager is primarily a non-adaptive real-time data acquisition and return mission, two types of science data acquisition and return adaptivity exist. Both types have been successfully used during VIM.

The first type of adaptivity is the recovery of a high rate PWS playback that is not captured with the initial playback. The response to the loss of a playback is to sequence a second playback prior to the time when data on the DTR is overwritten with newly recorded data. For normal baseline sequence recording of PWS data this allows 6 months to execute a second playback.

The second type of adaptivity is to increase the frequency of high rate PWS recordings and playbacks. This can be in response to a predicted termination shock crossing or increased plasma wave activity during cruise. An on-board sequence block allows increasing the high rate PWS recordings by sending a single command to the spacecraft. It can record one PWS frame about every nine hours over a period of two weeks or one additional frame per week for six months. It is now used in the latter mode on Voyager 1, essentially doubling the number of recordings and the resolution of the PWS high rate data.

Science Management

The Project Scientist coordinates with the Voyager Science Investigators, the science community, and other elements of the Project to ensure that the Project scientific objectives are met. The Science Steering Group (SSG) is chaired by the Project Scientist and consists of the Principal Investigators for the funded investigations. The SSG has the leading role in the overall optimization of the science return from the mission, and in resolution of conflicting science requirements. Members of the VIM Science Steering Group (the principal investigators) and their co-investigators are listed in Table 2.

Although funding for UVS and PRA has been discontinued by NASA, both data types are still being received. The UV data are made available to Jay Holberg at the University of Arizona, and the PRA data to Michael Kaiser at GSFC.

The principal investigators are responsible for analyzing their data and reporting their findings in a timely manner. They participate, as appropriate, in making these results available to the science community and to the general public. They present their results at science conferences, through news releases and via publications in the popular press and scientific journals. More than 160 refereed and non-refereed papers have been published since 2003. A list of published papers, by investigation, is available at
http://voyager.jpl.nasa.gov/science/bibliography.html

The principal investigators provide archival data to the National Space Science Data Center at Goddard. Since 2003 through July 2005, there were nearly 42,000 accesses to the archived data. Archived data can be accessed via the NSSDC Master Catalog at the following URLs:
http://nssdc.gsfc.nasa.gov/nmc/tmp/1977-084A.html
http://nssdc.gsfc.nasa.gov/nmc/tmp/1977-076A.html

A summary of data availability is accessible at the Sun-Earth Connection Data Availability Catalog at http://spdf.gsfc.nasa.gov/SPD/SPDTopMatrixNASA.pl In addition, a list of URL's, which point to science data, including those at the investigators' home institutions, is located at the JPL Voyager web site at http://voyager.jpl.nasa.gov/science/Voyager_Science_Data.html

Budget

Since the beginning of the Voyager Interstellar Mission, the project has continually adapted its operations concept and workforce in response to changes in funding levels. The project has undergone a continual transition from multiple specialized teams to a single operations team wherein each member performs multiple interdisciplinary functions. New, internally developed processes and efficiency enhancements have made this possible. In 2002-2003, the flight team was further reduced due to budget constraints. As a result, the current flight team consists of about 8 full-time equivalents. An independent review by an advisory group convened by the Director for Astronomy and Physics at JPL concluded that workforce below this level would result in unacceptable risks. This was based on the fact that the current budget level allows for only minimal spacecraft monitoring, immediate response to anomalies, a minimal degree of health reassessment, sequence augmentation and no training.

Concurrent to the reductions in the flight team in 2002 were reductions in the level of funding for science data processing, analysis and archiving. Because of the minimum level of funding, there has been a reduction in the number of graduate students and post-docs supporting the project, and the co-investigators are now performing much of the data processing and validation.

The guideline budget would have continued operations at the current minimum level, including costs to support the minimum flight team described above and a low level of project management support. The guideline budget includes costs for science center functions related to operating the instruments and performing quick-look data processing. Also included are limited science analyses required to ensure proper instrument operations and the validity of the data before they are archived. Science data analysis funds allow for limited science analysis and the publication and presentation of select papers, primarily of major science events.

However, because of growths in full-cost accounting at GSFC and new direct tailored services costs at JPL, the guideline budget, beginning in 2007, is deficient by about $400K per year. To meet the guidelines, operations would have to reduce by 1.0 FTE. There is no easy reduction, since the loss of any person means the loss of multiple functions. Though there would be a severe impact, a lesser impact would entail the loss of the ability to perform AACS trend analyses and currently ongoing analyses of spacecraft pointing degradation, including evaluation and upgrades of the HYBIC and H-Point Tables. We would lose long-term capability for trend analysis and, if pointing is not improved by the beginning of FY07, pointing degradation would result in degradation of science data reception.

The reduction in science funding in FY07 also corresponds to about 1 FTE, which is about 25% of that devoted to science analysis and will leave only ~3 FTEs devoted to analysis distributed over the five investigations. This will limit the analysis activities to a few topics at a time when Voyager is revealing many puzzling aspects of the heliosheath that require additional, not less, analysis and interpretation.

Within the proposed optimal budget, the descoped items described above would be reinstated. In addition, the optimal science budget would support ~2 additional FTEs in FY06 that would permit study of the broader range of topics outlined above and important augmentations in science center data products. Some of the benefits from this increased budget:

- Improve the quality and timeliness of Voyager

MAG data sent to the Voyager Investigators, other Scientists, and the NSSDC, and support our analysis and understanding of the MAG data.

- Complete development of capability to provide open access to all CRS data and improve capability to access data and documentation.
- Improve access to detailed CRS documentation to assist other investigators/students in using the data.
- Provide access to CRS data via web services to the SSSC Virtual Observatories.
- Enable more in-depth analysis of science data than that afforded in the guideline budget.
- Provide for more comparisons of solar wind features in the inner and outer heliosphere to understand the solar wind evolution.
- Increase participation of undergraduate and graduate students in data processing and analysis. This would introduce younger scientists into the space physics community.

Over the past year the Flight Team has identified more than seventy tasks that need to be accomplished, in addition to ongoing activities, to insure continued operations of the Voyager spacecraft at acceptable risk levels. These tasks may be described as items that would improve the operations infrastructure, replace and reduce the number of old workstations, update software modules to work with the newer computer systems and improve productivity and enhance personnel effectiveness to include cross-training and replacement training.

Important areas unattainable at present include acquisition and training of replacement personnel, detailed anomaly analysis, and improved operational efficiencies in several areas. Most of the electronic tools currently in use are ten or more years old. Many are in need of major upgrades or replacement. New technologies now make possible the development of intelligent tools to automate and reduce workloads and the potential for errors, improve spacecraft health monitoring, and provide for more confident long-range planning.

The optimal budget would provide funds to address the items deemed most important. One-time investments include:

- Software modifications required to migrate the data management system to modern computers,. This would enhance science data delivery and provide backup capability while reducing the number of workstations required for this task by 67%.
- Recompilation of the MARVEL program to operate on modern computers and to create a real-time backup.
- Development of a temperature estimation tool which would alleviate need for outside consultation and the attendant costs and would allow the team to make decisions about optimum and/or safe thermal balance when reconfigurations due to decline in power become necessary
- Analysis of spacecraft pointing degradation and implementation of necessary modifications to flight software
- Update the RTG model to refine lon-range power output predictions and better define mission extension potential.

There is also an ongoing need for an increase in personnel as follows:

- An increase in computer system administration support beginning in FY06 to implement the changes to workstations as described above and to allow Voyager to become up to date with AMMOS deliveries and remain in step with other missions. Current support levels have been insufficient to maintain this state and have resulted in significant workflow inefficiencies for Flight Team members.
- One FTE to initially provide for software and inherent systems administration support for non-AMMOS workstations and to develop Voyager real-time tools for the AMMOS environment, later to be cross-trained in other operations areas to provide backup and/or be a replacement as members leave the Flight Team. It is highly desirable that there always be a person in on-the-job training to eventually replace and minimize the loss of expertise with personnel departures.

Attributable Deep Space Mission Systems costs, though not part of the Voyager budget submission, are included in Table IV, Line 2a of Appendix 1. These are based on approximately 10 hours of coverage per day per spacecraft, using both the 34-meter and the higher cost 70-meter antenna. Direct Multimission Ground Systems and Services costs are included in Item 2a of Tables I and II. Estimated center Full Cost Accounting costs were obtained from Resource Analysts at GSFC and MSFC.

Voyager is the only mission currently exploring the far outer heliosphere. The spacecraft are capable of continued operations and are in position *now* to characterize the Sun's influence far away from the source. Until there are other missions to the outer heliosphere, Voyager will provide unique in situ information about this region of space. Voyager 1 has entered the heliosheath and Voyager 2 is poised to encounter the termination shock within the next few years. Continuation of the mission at the optimal level would allow for a more robust science mission that would answer fundamental questions about solar influences in the distant heliosphere, the interactions between the solar and interstellar media and the structure of the termination shock. Furthermore, it would provide for a more robust and lower risk operations environment and reinstate a small degree of flexibility for development of further enhancements and efficiency improvements to Flight Team processes.

EDUCATION AND PUBLIC OUTREACH OPERATIONS PLAN

Tying together the physical processes across the full scale of the heliosphere is possible because of the existence of a fleet of deep space missions that include the Voyagers. With the anticipation of the Termination Shock crossing, the Voyager E/PO program created partnerships and collaborations to enhance the breadth and knowledge of science, mathematics, and technology for K-14 education. The Voyager mission is contributing to a diverse set of programs that are improving basic scientific literacy. The redesigned and updated event-driven interactive web site, educator trainings and NASA Space Science Updates keep the mission status and new science discoveries at the fingertips of the public.

1. Engaging the Public

Voyager has a six-year partnership with the NASA/JPL Solar System Ambassadors Program that recruits volunteers from across the nation to conduct public events in their local areas. These events include exhibits, radio programs, concerts, town hall meetings and star parties in primarily rural locations. There are presently 459 Ambassadors (~40% added in 2 yrs.) in 50 states and Puerto Rico. Over the last fiscal year, Solar System Ambassadors have engaged a total of 169,457 participants in 230 events on the Voyager mission alone.

On June 17, 2005, the Voyager Project Scientist, Dr. Ed Stone, participated in an informal teleconference chat with Solar System Ambassadors. The topic of discussion was Voyager 1's entry into the heliosheath. The instant replay became available on June 25th for replay. The Ambassadors regularly evaluate the trainings which are sent to the Program Manager via email, "From Ron Schmitt in Minnesota: *"Thanks a TON for the telecon with Ed Stone. That was SUPER cool!! What great stories, and behind the scenes insight. I would buy a CD of that stuff, if I could. I LOVE hearing about all that goes on during the missions ˆ what choices they made, were they good ones, what happened when they weren't, what totally surprised them... Excellent, excellent stuff. Real human beings exploring the galaxy and all that. Please thank Ed for us".*

Voyager E/PO partners with NASA's Space Place Program (~~http://spaceplace.jpl.nasa.gov~~), by providing educational products. Voyager and SEC literature is distributed to more than 300 rural museums, libraries and planetariums and amateur astronomy clubs for K-6 students. The program also produces articles for Astro Club. Space Place has a formative evaluation process. Teacher-advisors evaluate each product for age appropriateness, appropriate choice medium, and the ability of the proposed material to support concepts typically covered in the formal education setting. In addition the Program Evaluation Research Group (PERG) is in the process of conducting a summative program-wide evaluation.

Annually Voyager supports the JPL Open House which welcomes over 50,000 people over a two-day period. Exhibits, models and handouts are made available for general public dissemination while team members answer questions regarding the mission and its various science objectives.

Figure 1: Voyager At JPL Open House

1.1 ~~World Wide Web~~

The JPL Voyager website at ~~http://www.voyager.jpl.nasa.gov~~ is accessed by ~ 60,000 unique visitors per month. In the month of June (after the AGU press release of Voyager 1's entry into the heliosheath) the site received over 100,000 visits. Anticipating the high demand for Voyager information, Dr. Ed Stone worked with JPL audiovisual team to produce a special Quicktime movie for the website that tells the story of Voyager 1's historical crossing of the Termination Shock. The site is updated as needed with new educational components, data, facts and to be compliant with the Rehabilitation Act which requires Federal agencies to make their electronic and information technology accessible to people with disabilities (Section 508).

1.2 Media Relations

Over the past 2 years the Voyagers have been involved in several media related activities. In November 2003, NASA hosted a Space Science Update. Press Release 03-354, titled "Voyager Approaching Solar System's Final Frontier", generated over 27 news features around the world. In July 2004, Voyager Science Team members participated in a NASA Virtual News Briefing regarding the Halloween 2003 record-shattering solar storms that reached Voyager, over eight billion miles away, a half year later. Over 30 reporters from companies like Sky & Telescope, Associated Press, Washington Post and National Geographic Magazine listened and logged into the news briefing. The same briefing was later featured in an article on the Science@NASA web site at http://science.nasa.gov/headlines/y2004/13jul_solarblast.htm

During the Termination Shock Crossing announcement, Tim Hogle, Voyager Operations team member, gave interviews for Los Angeles television stations KABC and KNBC, and the Sandusky Ohio Register.

On June 14, 2005, Drs. Stone and Krimigis participated in a 30-minute interview program sponsored by AARP on NPR, called Prime Time Radio. The program was titled "Voyager at 30".

2. Informal Education

LA's BEST - Better Educated Students for Tomorrow - was created in 1988 by Mayor Tom Bradley to address an alarming rise in the lack of adequate adult supervision of children during the critical hours between 3 and 6 p.m. From its inception, LA's BEST has maintained a balance of high quality standards for education, enrichment, and recreation. 130 elementary schools sites in the Los Angeles School District primarily minority based inter-city schools, are involved in the program. During this year's on-site visit by Voyager Team members, grades 3-5 students participated in discussions about the solar system, stars, black holes and the Voyager mission. LA's BEST has commissioned the National Center for Research on Evaluation, Standards and Student Testing (CRESST) and the Center for the Study of Evaluation (CSE) at the University of California, Los Angeles, to evaluate the program and to measure its impact both quantitatively and qualitatively.

Figure 2: LA's Best - El Dorado School

On December 3, 2004, Professor Larry Josbeno, gave a Voyager presentation at the Corning Community College Observatory in New York. The presentation was sponsored by the Elmira/Corning Astronomical Society and was attended by approximately 60 students. The Voyager Project supplied Dr. Josbeno with copies of the Voyager Educational CD-ROM, "**Unraveling the Secrets of the Solar Wind**", planetary tour slides, educational wallsheets and bookmarks for this presentation.

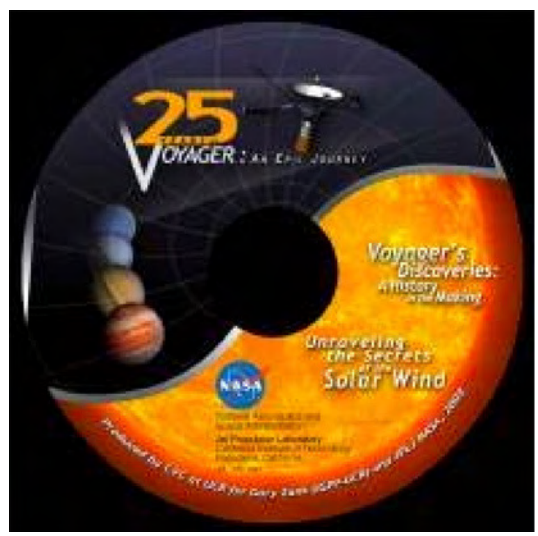

Figure 3: Voyager Educational CD-ROM

On June 2, 2005, the Voyager Project participated in the Space Day activity at Longfellow School in Riverside, CA, which was co-sponsored by Lockheed -Martin Space Systems and the Traveling Space Museum. Approximately 400 students participated in 20 minute activities and viewed Voyager, Genesis, Stardust and DSN exhibits.

The Voyager Project Manager accepted an invitation from the University of Southern California to present a Voyager overview to 75 Honors Engineering students. The event took place on February 11, 2005.

Figure 4: Orange County Astronomers Meeting Notice

Voyager team members regularly participate in local community events. Tim Hogle gave a presentation on Voyager's journey toward interstellar space at the Orange County Astronomers meeting on September 9, 2005. Approximately 250 amateur astronomers attended the meeting More information is available at http://ocastronomers.org/e-zine/monthly_meetings/

Former Voyager Team member, Donald Heller, gave a Voyager presentation to 60 first graders at Pinecrest Elementary School. The students had an opportunity to see a scale model of the spacecraft. Heller also used a "mini spacecraft" - a platform about the size of coffee mug, with a color video camera on a scan platform, 10 cm antenna, 2.4 GHz battery powered transmitter – to demonstrate how a spacecraft would take pictures and transmit them to the DSN. The "DSN" receiver was about the size of a VHS player, which was connected to the school-provided television.

Technical Specialist and After School Educator, Drew Koning requested the on-line Voyager powerpoint presentation to use in his after-school program, "NASA Missions", at the American Museum of Natural History in New York. The program was scheduled from January 12 – February 9, 2005 for students in grades 9-12. More information is available at their web site at http://www.amnh.org.

3. ENGAGING THE PUBLIC - PLANS FOR FY06-FY08

Voyager will continue to support the NASA/JPL Solar System Ambassadors Program. The project will facilitate a minimum of one training session each year for new Ambassadors and additional training will be conducted to support significant mission milestones. Ambassadors will be exposed to key personnel while examining new science results from Voyagers 1 and 2.

The Voyager E/PO Lead is working with NASA's Space Place and Tony Phillips to develop an Astro Club and Kids Newspaper article on Voyager 1's Crossing of the Termination Shock. The articles will be produced in both English and Spanish. Additionally, E/PO materials and exhibits will be rotated two times per quarter to participating Space Place partners, which include rural libraries, zoos, science centers, and museums.

"Community Nights": Working in partnership with the Arizona State University Mars K-12 Education Department, Voyager will continue to participate in the re-development of Solar System kits. These kits have been beta-tested by more than 100 girl scout troops and are presently scheduled for revision and updates for introduction to the GSUA Nationwide. The portable exhibits will be loaned to educational facilities, community organizations and other NASA EPO partners.

3.1 World Wide Web

The Voyager web site will continue to be updated quarterly. Plans include new educational activities, press releases and mission status reports.

4. INFORMAL EDUCATION

The Voyager project plans continued support for Presidential Executive Order 13021: Tribal College, Tribal Pre College Initiatives by providing opportunities for K-12 teacher training, enhancing curriculum and engaging students in NASA related career fields, The project will work with the JPL Tribal College Initiative in the Minority Education Initiatives in the Education and Public Outreach Office.

The Voyager Team has agreed to support Eliot Middle School Tutoring program. We will provide literature, educational wall sheets and tutors. Tutors meet with the students twice weekly, offering one-on-one volunteer tutors for 35-45 students per session.

4.1 Conferences/Workshops

Voyager will ontinue to support educational conferences requiring NASA Center presence, i.e., NSTA, CSTA, and Space Congress. Educator Paul Williams has submitted a Voyager proposal to the National Science Teachers Association National Conference which will meet in Anaheim on April 6-9 of 2006

5. Formal Education

The Voyager Project Office, with support from the science teams, proposes an educator workshop at JPL for the NASA Explorer School Program. This workshop will consist of lectures from team members and classroom activities, with the goal of providing educators an explanation and understanding of the termination shock crossing and its significance.

6. E/PO Products

The project will continue to develop products to support the education and public outreach programs. These will include, as appropriate, brochures, decals, educational content for web sites, and packages for educational conferences and workshops. Educational products will be distributed through the NASA Education Resource Centers and through distribution to schools involved in the various E/PO programs in which the Voyager project is involved.

7. E/PO Budget

By participating with other missions at JPL and with the Sun-Earth Connection Forum, the project has been able to leverage its limited E/PO funds. The requested E/PO funds will be used to participate in the various partnerships/subcontracts that the Voyager Project will be involved in, such as Solar System Ambassadors, The SpacePlace, and Educator Consultants. The Voyager Project will purchase educational wall sheets and bookmarks for NASA supported educational conferences. Activity supplies and tools, such as Star Finders, lithographs and evaluation forms will be purchased for hands-on activities. In anticipation of Voyager 2's Termination Shock Crossing in the next 3-5 years, the project will be working closely with the NASA/JPL Media Relations to create new animations, science updates and press releases. Travel funds are requested to attend the NASA supported conferences and science meetings where Voyager is represented. Direct Labor costs will cover the Voyager web site updates and audiovisual support.
The optimal proposal would include additional funds to create additional products and to increase project participation in other education and public outreach venues.

	FY06	FY07	FY08	FY09	FY10
1. Direct Labor (salaries, wages, and fringe benefits)	8000	8000	8000	8000	8000
2. Other Direct Costs:					
a. Subcontracts	15000	15000	15000	15000	15000
b. Consultants	2000	2000	2000	2000	2000
c. Equipment					
d. Supplies	18000	18000	18000	18000	18000
e. Travel	7000	7000	7000	7000	7000
f. Other					
3. Facilities and Administrative Costs					
4. Other Applicable Costs					
5. SUBTOTAL--Estimated Costs	50000	50000	50000	50000	50000
6. Less Proposed Cost Sharing (if any)					
7. **Total E/PO Estimated Costs**	50000	50000	50000	50000	50000

Appendix 1
List of Acronyms

Acronym	Meaning
$xsxK	Thousands Of Dollars
AACS	Attitude & Articulation Control Subsystem
ACE	Advanced Composition Explorer
ACR	Anomalous Cosmic Ray
A-D	Analog To Digital (Converter)
AMMOS	Advanced Multi-Mission Operations System
AU	Astronomical Unit
B	Magnetic Flux
BEST	Better Educated Students for Tomorrow
BML	Backup Mission Load
CCS	Computer Command Subsystem
CMIR	Corotating Merged Interaction Region
CRESST	Center for Research on Evaluation, Standards & Student Testing
CRS	Cosmic Ray Subsystem Experiment
CSE	Center for the Study of Education
CST	Canopus Star Tracker
CSTA	California Science Teachers Association
DOY	Day of Year
DSN	Deep Space Network
DTR	Digital Tape Recorder
EDR	Experiment Data Record
ENA	Energetic Neutral Atom
E/PO, EPO	Education & Public Outreach
FDS	Flight Data Subsystem
FPA	Fault Protection Algorithm
FTE	Full-Time Equivalent
GCR	Galactic Cosmic Ray
GMIR	Global Merged Interaction Region
GSFC	Goddard Space Flight Center
H	Hydrogen
HCS	Heliospheric Current Sheet
He	Helium
HGA	High-Gain Antenna
HISCALE	Heliosphere Instrument for Spectra, Composition, and Anisotropy and Low Energies
HP	Heliopause
HSH	Heliosheath
HYBIC	Hybrid Buffer Interface Circuit
IBEX	Interstellar Boundary Explorer
IMF	Interplanetary Medium
IMP	Interplanetary Monitoring Platform
ISCRS	Interstellar Cosmic Ray Spectra
KeV	Thousands of Electron Volts
K-12	Kindergarten through 12th grade
LECP	Low-Energy Charged Particles Experiment
LISM	Local Interstellar Medium
MAG	Magnetometer Experiment
MARVEL	Monitor/Analyzer Of Real-Time Voyager Engineering Link
MHD	Magnetohydrodynamics
MeV	Million Electron Volts
□G	MicroGauss
MIR	Merged Interaction Region
NASA	National Aeronautics & Space Administration
NSSDC	National Space Science Data Center
NSTA	National Science Teachers Association
nuc	Nucleon
PLS	Plasma Science Experiment
PRA	Planetary Radio Astronomy
PWS	Plasma Wave Subsystem Experiment
QEDR	Quicklook EDR
RMS	Root Mean Square
RTG	Radioisotope Thermoelectric Generator
SAMPEX	Solar Anomalous and Magnetospheric Particle Explorer
SSSC	Sun-Solar System Connection
SSG	Science Steering Group
SW	Solar Wind
SWICS	Solar Wind Ion Composition Spectrometer
TS	Termination Shock
TSP	Termination Shock Particles
UT	Universal Time
UVS	Ultra-Violet Spectrometer
V	Velocity
V1	Voyager 1
V2	Voyager 2
VAMPIRE	Voyager Alarm Monitor Processor Including Remote Examination
VIM	Voyager Interstellar Mission